Historical Case Studies: Teaching the Nature of Science in Context

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ABSTRACT: In this article I research the use of the historical perspective in the teaching and learning of science. I start from the premise that pupils' understanding of the nature of science is as important as their understanding of current curriculum content. The fact that rigorous assessment of this aspect of science is difficult should not lead science educators to undervalue its importance. The research demonstrates that it is possible to assess qualitatively the effectiveness of historical material in achieving desirable attitudes while simultaneously measuring quantitatively the degree to which this approach influences understanding of the conventional science curriculum. The concept of the atom and the periodic pattern in the atoms of the elements is the subject of a series of historical episodes in which it is clear that human creativity and the power of the imagination lead the way to giant strides in scientific knowledge. By tracing the development of atomic theory from the Greeks to the present day I show that pupils can appreciate that the nature of science itself is in flux. The research involves two parallel groups of 14-year-olds of similar abilities and scientific background. The first group studied a unit in which a substantial amount of historical material was incorporated. The second group studied a unit covering identical scientific content but without any reference to history. The results show that there is no difference in understanding of contemporary science content between the two groups despite my hope that the historical perspective would lead to a firmer grasp of concepts. However, it does allay the fears of those who suspect that the introduction of nonessential curriculum material could weaken pupils' grasp of essentials. In regard to pupils understanding the nature of science I identify several advantages resulting from the historical approach. When pupils see the challenges within their historical context it counteracts the patronizing attitude that many pupils adopt toward past scientists, viewing them, as they do, from their superior vantage point in history. I found that an appreciation of the creative role played by the great scientists of the past was an antidote to the excessive realism and determinism typical of many pupils. Their image of the certainty of scientific knowledge is challenged but they see that the uncertainty of a scientific theory does not necessarily nullify its usefulness in making further progress possible. Finally, I make a case for the historical treatment of theory as a means of demonstrating to pupils that scientific knowledge can range from the highly speculative to the universally accepted and that a critical assessment of any scientific knowledge claim can be made accordingly. © 2000 John Wiley & Sons, Inc. *Sci Ed* **84:**5–26, 2000.

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INTRODUCTION

The evidence so far suggests that, far from encouraging pupils to consider the nature of science, teachers rarely consider their own stance in this regard. A document published by the UK's Association for Science Education (1979) stated that "most science teachers, who are themselves products of a science education system that places a high premium on scientific knowledge and pays lip service to the history and philosophy of science, share with many practising scientists a scant understanding of the nature of scientific knowledge." Hodson (1986) claimed that many teachers subscribed to an outdated philosophy of science and that there was an urgent need "for much greater consideration of philosophical issues in teacher education programmes."

Where pupils do attain a view of the nature of science in science lessons it is often conveyed unconsciously by the actions, assumptions, and language of the teacher. It is this "hidden science curriculum" which Hodson thinks carries the major message about the nature of science and could well be influential in determining whether pupils subsequently take up optional science courses. He has argued the case for a more explicit treatment of the nature of science. He maintains that teachers should identify desirable attitudes and dispositions to science and deliberately incorporate suitable aspects of science in the curriculum in order to bring about the desired outcome. The present research constitutes a conscious attempt to focus on some philosophical issues and to bring them to the forefront of the curriculum. In particular, I was interested in getting pupils to think about the ways in which scientific knowledge has grown.

The program of study for 11–14-year-olds in Science in the National Curriculum (DES and Welsh Office, 1995) in the UK acknowledges the importance of "The nature of scientific ideas" but omits specific examples of historical cases. The program of study states that "Pupils should be given opportunities to:

(a) consider the importance of evidence and creative thought in the development of scientific theories;
(b) consider how scientific knowledge and understanding needs to be supported by empirical evidence;
(c) relate social and historical contexts to scientific ideas by studying how at least one scientific idea has changed over time."

At the end of year 9 (age 14), all pupils in UK schools are examined in the core subjects of English, Math, and Science using Standard Assessment Tasks (SATs). These are examined externally and the results are made available to the public. In the UK National Curriculum, the central government has shown a clear preference for aspects of science that lend themselves to rigorous testing and clearly defined levels of pupil attainment (Solomon, 1991). Unlike the rest of the National Curriculum in science no effective testing of the aspects of science shown above is made in the SATs. It is not surprising, therefore, that the School Curriculum and Assessment Authority reported in *Monitoring the School Curriculum* (SCAA, 1996) that "Some teachers feel that some aspects of science not readily assessed by the end of key stage tests are becoming undervalued." They state that "Future monitoring will include a focus on the following questions," including "How are schools ensuring a balance in their teaching between aspects that are tested and the development of scientific abilities which are less readily tested?" The nature of science is clearly in the latter category.

An understanding of "the nature of science" is relatively difficult to examine but that fact alone should not justify its exclusion from school tests. (It is, after all, a difficulty inherent in many other subjects forming part of the school curriculum.) In a crowded curriculum the fate of all nonexamined items is that they are given passing reference or, more likely, neglected altogether. This danger is given added emphasis by the competitive edge that the publicity surrounding the SATs has brought. In the desire for success and recognition the temptation for schools is to "teach to the tests." If "testability" is discarded in favor of less superficial pedagogical criteria like "motivating power" or "capacity to facilitate critical thinking" a strong case can be made for a "frontline" role for the nature of science.

In a previous case study (Irwin, 1996), I undertook some qualitative research into the extent to which the revolution in the theory relating to combustion could influence pupils' understanding of the way in which scientific knowledge grows. The story of the overthrow of the phlogiston theory is a suitable means of showing how scientific theories change. That historical episode is an appropriate means of counteracting the prevailing view of science as a gospel of unassailable "truths" and points to the danger of scientific dogmatism. However, my research also illuminated a popular misconception of the *origins* of scientific ideas. It was clear from the results of that study that many pupils associate the growth of scientific knowledge largely with "discovery" and have little appreciation of the part played by human imagination as a source of powerful ideas.

RATIONALE

Contribution to Scientific Literacy

Bybee et al.'s (1991) case for an increased emphasis on the nature of science arose from their definition of scientific and technological literacy:

1. The scientifically literate person understands the nature of modern science, the nature of scientific explanation, and the limits and possibilities of science.
2. The technologically literate person understands the nature of technology, the nature of technological solutions to human problems, and the limitations and possibilities of technology.
3. The scientifically and technologically literate person understands that the natures of science and technology as well as their interrelationships have changed over time.
4. The scientifically and technologically literate person understands that science and technology are products of the cultures within which they develop.
5. The scientifically and technologically literate person understands that the roles and effects of science and technology have differed in different cultures and in different groups within these cultures.
6. The scientifically and technologically literate person understands that technology and science are human activities that have creative, affective, and ethical dimensions.
7. The scientifically and technologically literate person bases decisions on scientific and technological knowledge and processes.

It is my contention that the understandings 1–7 just listed cannot be achieved by school pupils if their science curriculum is restricted to the "rhetoric of conclusions" (Schwab, 1964). As Kyle (1997) noted, "Students ought to experience the how of scientific enquiry, rather than merely being exposed to what is known about and by science." My interpretation of the "how of scientific enquiry" includes the intellectual struggles faced by scientists within the appropriate historical context. My proposal is that items 3, 4, 5, and 6 can be realized most effectively using historical cases and that some of these cases could contribute to the achievement of item 7.

The problem, as stated by Bybee and coworkers, is that “Nowhere is the student likely to encounter a cohesive view of the ways in which the intellectual development of the sciences and the resolution of problems by technology shaped history and were in turn shaped by it.” There is clearly scope, therefore, for research into the effectiveness of historical themes, in bringing about this “cohesive view.” According to Bybee et al. (1991), “. . . it is important for people to understand science as a key element in intellectual history — the achievements of the human mind” and “. . . some episodes in the history of the scientific endeavour are of surpassing significance to our cultural heritage.” I believe that the growth of chemical knowledge from Dalton’s Atomic Theory in 1807 to the publication of Mendeleev’s Periodic Table (1871) includes a series of such episodes.

Rationale for the Methodology of Research

In designing the study I was influenced by the *Harvard Case Histories in Experimental Science* (Conant, 1970), the general aims of which had similarities with my own, even allowing for the different context. The case histories described by Conant were designed primarily for students at Harvard University majoring in the humanities or the social sciences. The rationale for the project was that such students require an understanding of science that will help them relate developments in the natural sciences to those in other fields of human activity. In Conant’s view this “demands an understanding both of the methods of experimental science and the growth of scientific research as an organised activity of society.” The aim was to combat the layman’s “fundamental ignorance of what science can or cannot accomplish” and to achieve an understanding of science independent of any knowledge of scientific facts or techniques.

Unfortunately, a direct study of the methods of modern science would present great difficulties for the layman because he lacks the large accumulated background of technical information essential to the task. The same problem confronts school pupils at the age of 14. The great advantage of studying an episode from the history of science (when the state of knowledge was relatively undeveloped) is that the concepts involved are more likely to be within the compass of the student. Knowledge of the way in which the episode unfolds provides an insight into the workings of modern science where the pupil’s state of knowledge is probably insufficient to cope with contemporary work in the field.

Conant’s target group was well defined. They were committed nonscientists, all of whom, by definition, had rejected science as a choice of career. My target group consisted of a few pupils who would go on to further education in science and take up scientific careers, together with a much larger number who would be the nonscientists of the future. The future scientists, as Kuhn (1970) pointed out, will ultimately obtain an accurate picture of the workings of modern science by actually doing research. In this sense, I felt, like Conant, a greater responsibility to the future nonscientists in providing a more accurate account of scientific progress. Nevertheless, at this stage of their school careers, all the pupils are potential scientists. I was, therefore, concerned that the human achievement described in this episode would inspire and motivate *all* the pupils and that, hopefully, this could have some bearing on pupils’ choices in regard to further education. Conant wrote, “The purpose of the case histories presented in this series is to assist the reader in recapturing the experience of those who once participated in exciting events in scientific history.” I embarked on this study in a similar spirit, albeit tempered by the knowledge that pupils’ have certain expectations of science lessons that might conflict with my plans

(Lakin & Wellington, 1995). However, from my previous research (Irwin, 1997), I was confident that the personalities and stories associated with the chosen episodes would appeal more to typical 14-year-olds than the more conventional, “final form” treatment. (The latter term was applied by Duschl [1994], to the kind of science curriculum that presents science as a body of knowledge without a past and that ignores the means by which scientific knowledge has been obtained.)

It is this “human factor” in the advance of science that has often been neglected by the authors of science textbooks (Irwin, 1996) in their concern to catalog “what we know” rather than “how we know.” By setting the problems in their historical context, emphasizing that the scientists involved lacked the benefit of hindsight, and bringing out the boldness and inspired guesswork that characterized their work, this personal element can be restored. Like Conant, I wanted to dispel the myth that scientific theories emerge from a careful examination of all the facts followed by a logical analysis of various ways of formulating a new principle.

I was also influenced by a year-long classroom study by Solomon et al. (1994), which examined how pupils’ views of the nature of science changed when some of their learning materials were historically situated. Five classes with an age range of 11 – 14 years were involved in this research and the evidence comprised pre- and posttests, questionnaires, and interviews. The researchers rejected the idea that epistemology is the kind of disembodied knowledge that could be abstractly encoded in the memory. They found that stories from history seemed to have provided alternative images of scientific epistemology that generated more reflection. One notable effect of such stories was that there was a substantial increase in the number of pupils who thought that scientists set out to seek explanations rather than make discoveries. They concluded that stories of the actual activities of science are memorable enough to create a valuable library of epistemological ideas in the minds of young pupils.

Cultural Significance of Science

Driver et al. (1996), in making the case for the nature of science as an essential component of scientific literacy and therefore of the public understanding of science, include the *cultural* significance of scientific achievement as a primary argument. Accordingly, science education should emphasize the major landmarks in our understanding of the natural world, and the major figures and events in the history of science. In Driver et al.’s view, this would inevitably require an understanding of epistemological issues and ideas, and would raise questions, of a sociological kind, about the relationship of ideas and their origins to the social context in which they emerge. They also contend that an understanding of the nature of science promotes successful learning of science. They point to the danger of pupils’ failure to recognize the conjectural nature of theories and to understand where an explanation comes from. In their view the separation of theories from their origins discourages a skeptical approach by pupils, leading to a passive learning style, which is inefficient.

Support for the cultural argument also comes from Millar’s (1996) outline of the kind of science curriculum that would most likely promote public understanding. One of the arguments he presents as a means of improving the curriculum is that we should ”do less but do it better.” He maintains that there are some powerful mental models in science — ideas that are cultural products of significance and beauty — and that a knowledge and understanding of them is life-enhancing. His criteria for choosing which models to include in the curriculum are “their cultural significance and their role in underpinning an understanding, in broad terms, of issues which may enter the public domain or of personal actions." Among the models he nominates for inclusion is "the atomic/molecular model of matter (emphasizing the scientific understanding of chemical reactions as rearrangements of matter)."

Rationale for Choice of the Atomic Theory as Historical Theme

The concept of the atom had its origins in philosophical speculation, the emergence of which can be traced back to the Greeks of the sixth and seventh centuries B.C. (Lloyd, 1982). The establishment of democracy in some Greek city-states encouraged participation and debate on political issues, a practice that helps explain the tradition of debate on a wide range of philosophical questions. Natural philosophers sought explanations for the causes of natural phenomena. They were dissatisfied with explanations resting on supernatural authority and so began a quest for rational explanations that could be argued in free debate. The measure of the their achievement is the advance they made in grasping the problems.

Among these was the problem of change. For instance, the Greeks were aware that nature regenerated itself. Although leaves were consumed each autumn new ones appeared in the spring. There was change and yet there was regeneration. In the fifth century B.C. the Greek atomists claimed that there is change on a macroscopic scale but not on a microscopic scale. The main assumption of their atomic theory was the existence of tiny, indivisible, and indestructible particles called atoms. The atoms were invisibly small, completely full of matter, had different shapes and sizes, acted with each other by direct contact, and were in continuous motion. Apart from atoms only void existed. Atoms in motion coming together into combination and recombination, or going apart causing decay of bodies, produced continuous change of matter. Atoms and void were the only ingredients of nature. The explanation for change was therefore that, although individual things decay by losing their atoms, these could come together again to form something new.

The chief characteristic of this early form of science was the abstract nature of the debate. It was not the empirical data that counted in support of a theory, so much as the economy and consistency of the arguments on which it was based. Popular acclaim was to be gained by natural philosophers through the success of their logic and rationality in debate rather than their practical skills. Further development of the theory took place in a completely different historical context in the era of the "chemical revolution," during which time the importance of empirical evidence in support of theory became paramount. The research I describe seeks to contrast the nature of science in these two eras.

Conant (1970) believed that the development of the atomic theory at the beginning of the nineteenth century was an example of the way in which an immediate interest in the "practical arts," in this case meteorology, could lead to the formulation of a more generalized conceptual scheme. The crucial historical factor was the combination of methods of experimentation developed in the "practical arts" with deductive methods of reasoning developed in mathematics.

The essential features of the modern atomic theory are generally attributed to John Dalton. As part of his meteorological investigations he tried to solve the problem of why the gases in the atmosphere are so thoroughly mixed despite the differences in their specific gravities. His reading of Newton's *Principia*, together with the results of Boyle's experiments on the pressure/volume relationship in gases, led him to the assumption that gases consist of particles repelling each other with a force proportional to the distance between them. He also accepted the contemporary theory of heat, according to which each gas particle is surrounded by a sphere of caloric fluid, endowed with the quality of self-repulsion. Finally, from his own experimental results he concluded that the individual particles of one pure gas must differ in size from those of another gas.

The application of these assumptions to his original problem enabled Dalton to conclude that mutually repulsive contiguous particles of several different sizes would not be in equilibrium in strata, thus explaining the thorough mixing of the gases in the atmosphere. More significantly, it was this very work that led Dalton to the concepts of the chemical atom, atomic weight, and the Law of Multiple Proportions. Despite these ultimate achievements, "*each and every one of his steps as just given was factually wrong or logically inconsistent*" (Holton, 1988). Newton's proof was a mathematical exercise, not applicable to real gases. The calorific theory of heat contained inherent contradictions. Dalton's own experiments were often inadequate to support his conclusions and his final conclusion did not even follow from his own premises. Indeed, many of Dalton's contemporaries doubted the validity of his basic assumptions and, while they would admit the *instrumental* usefulness of atoms, they remained skeptical about the *real existence* of these atoms (Conant, 1970).

AIMS OF THIS RESEARCH

The aim of the case study I describe is to show pupils that there are episodes in the history of science that illustrate the the power of the human mind to make brilliant and bold conjectures on the basis of little or no direct evidence, but which can lead to gigantic strides in scientific knowledge. My previous research (Irwin, 1997) indicated that pupils have an image of science that is highly determined; the "truth" is out there and scientific progress consists of discovering it. I designed the curriculum unit with the explicit aim of providing opportunities for pupils to appreciate that scientific progress does not amount simply to a series of incidental discoveries. The growth of scientific knowledge is characterized by feats of imagination and creativity that account for sense-data and yet go beyond these to establish powerful models and unifying principles.

It was also evident from my previous research that, far from recognizing the work of pioneering scientists as inspirational, many pupils (in accordance with many textbooks) adopt a patronizing attitude. Typically, textbook authors assess the work of past scientists in terms of their contribution to what we now regard as established knowledge—the so-called Whig approach to history (Brush, 1974). With the benefit of hindsight it is tempting to judge the work of previous scientists as misdirected, incomplete, or simply wrong. It is not surprising that pupils pick up this note of condescension, whether from textbooks or teachers. My intention was to counteract this tendency by giving pupils opportunities to appreciate the problems faced by our scientific predecessors in the context of the knowledge available to them at the time.

My hope was that pupils who had gained an appreciation of the challenges and difficulties faced by scientists of a different era and who were aware of the context of scientific advance would have a firmer foundation on which to base their own understanding of theory. Support for this aim is provided by Monk and Osborne (1997) who contended that "The study of scientific ideas in their original context of discovery will help to develop students' *conceptual* understanding:

- Because historical thinking often parallels their own.
- Because the now accepted scientific idea was strongly opposed for similar reasons to those proffered by students.
- Because it highlights the contrast between thinking then, and now, bringing into a sharper focus the nature and achievement of our current conceptions.

I felt it was important to provide evidence, at least, that the historical approach did not detract from pupils' understanding of scientific concepts even if my results did not indicate any positive gain in this regard. The latter aim is important in order to reassure science teachers that in giving due emphasis to this nonexaminable part of the national curriculum they are not also jeopardizing the pupils' understanding of examinable science content. Given the pressures of accountability and the competitive atmosphere that currently exists, it would be unrealistic to expect science teachers to adopt any curriculum material unless they were entirely convinced that there was no threat to examination results.

RESEARCH METHODOLOGY

In carrying out classroom research into improving pupils' understanding of the nature of science using historical cases my choice of target groups was determined by the following conditions:

1. I needed to teach two groups of similar age, ability, and ease of management. One group would be taught the unit with a historical perspective and the other would act as a control.
2. The two groups had to have the same background knowledge in science, with some previous knowledge of elements, mixtures, and compounds and the particulate nature of matter. These topics are covered in years 7 and 8 (i.e., at the age of 11–13 years) in my school.

Whitton School is a mixed secondary school (school years 7–11, age range 11–16) in an outer London borough with slightly higher than the UK average number of pupils with special educational needs (i.e., needing extra support in their learning). Achievement in public examinations at 16+ is slightly lower than the national average. I judged that year 9 pupils would be most suitable for this research because:

(a) They had the necessary foundation knowledge.
(b) They were likely to be motivated by the events and personalities involved in the episodes.
(c) They had not yet made a decision for or against science in regard to their future studies.

It is worth noting here that there is currently a climate of competition among UK secondary schools for their new “intake” each year, when pupils make the transition from primary school to secondary school at age 11. The year 9 SATs results may well influence parents in making the choice of secondary school for their children. Set against this background it is not surprising that my colleagues were concerned that my research would not adversely affect pupils' performances in the science SATs. On the positive side, these circumstances added some urgency to my work.

Pupils are taught in three ability bands in year 9 (age 14) and selection for them is based on year 8 attainment as reflected in test results and teachers' reports. My timetable for the academic year 1996–1997 included two middle-band year 9 classes, each consisting of 25 boys and girls. For the purposes of my research one of these groups was designated the “historical theme group” (HTG) and the other was designated the “final form group” (FFG). In order to verify that both groups were starting from approximately the same base in their understanding and knowledge of this topic I gave them a pretest (see Appendix I). Each group was then taught eight lessons on the topic “Atoms and the Periodic Table” without any extra time for the historical content of the HTG unit.

In lessons 1–4 of the HTG unit there was an emphasis on theory development in a historical context. The corresponding lessons for the FFG presented the theories in logical order without any reference to history (see Appendix III). Lessons 5–8 were identical for both classes and consisted of a conventional treatment of the periods and groups of the Periodic Table. The last lesson consisted of a posttest with no historical content (see Appendix II) and a questionnaire, suitably amended for the FFG where necessary (Fig. 1 shows the format of the case study).

A distinguishing feature of this work is that it is a piece of action research by an individual teacher in a UK secondary school. The design of the unit, the classroom research, and the analysis of the results were carried out by the author. A distinct advantage of this work is that it does not suffer from the research/practice gap that affects many of the curriculum innovations in school science (Pekarek, Krockover, & Shepherson, 1996). This problem was also noted by Monk and Osborne (1997), who recently lamented the fact that science education had been "highjacked by academia." They pointed out that "too many of the justifications for the use of the history of science are provided by historians and philosophers with little knowledge of primary or secondary pedagogy rather than by teachers with a reasonable of history and philosophy." They revealed that "a count of the last six journals shows that of the 54 contributing authors only one is a practising teacher." This research may go some way to restoring the balance.

The form of my research was partly determined by circumstances. The research had to be an integral part of my teaching. None of my colleagues felt sufficiently confident with the materials to get involved although they sympathized with my philosophy. The very nature of the outcomes I was looking for were difficult to assess quantitatively and, given the small sample to which I was restricted, the results could hardly have been statistically significant. I therefore decided on qualitative methods of research for the main investigation on improving pupils' understanding of the nature of science. As a teacher-researcher I made my own observations. Unlike the kind of research done by Solomon, Scott, Duveen (1996), and colleagues, my findings were not complicated by the affect of a third party observer. The pretest and posttest were included to compare the learning of conventional science content by the two groups.

The pupils who took part in the discussion were invited as a result of any interesting comments, oral or written, they had made during the study. I wanted to give them the opportunity to amplify those views. I selected four pupils from the HTG and four from the FFG to constitute a focus group (in the event only three of the FFG students took part). The disadvantage of being a teacher-researcher in such a discussion is that it is difficult to *refrain from teaching* when a more objective inquiry mode is more appropriate. Hence, the transcript of the tape could be viewed as a series of leading questions in which I invited the answers I was looking for or in some cases provided those answers myself. In retrospect, my role here should have been less the teacher and more the objective researcher.

At the time I saw this part of the research, which was conducted 2 days after the last lesson, as a means of underlining and sharpening the understandings and attitudes I had already detected during the lessons and by means of the questionnaire. Solomon et al. (1996) also recognized the dual nature of the role needed in this kind of action research. During lessons they adopted a collaborative role in helping and supporting the teachers, but, in order to collect objective and impartial evidence of pupil progress, they had to restrict their role to *interviewer* rather than helper once the lessons were over (Fig. 1). One of the problems I met was that some conscientious members of the FFG noticed, through informal discussions with their friends in the parallel group, that there were aspects of the unit that they were not being taught. Despite my best intentions in avoiding "cross-contamination" of historical references I could not prevent such pupils producing homework that demonstrated very thorough research into the historical aspects of the topic. It caused

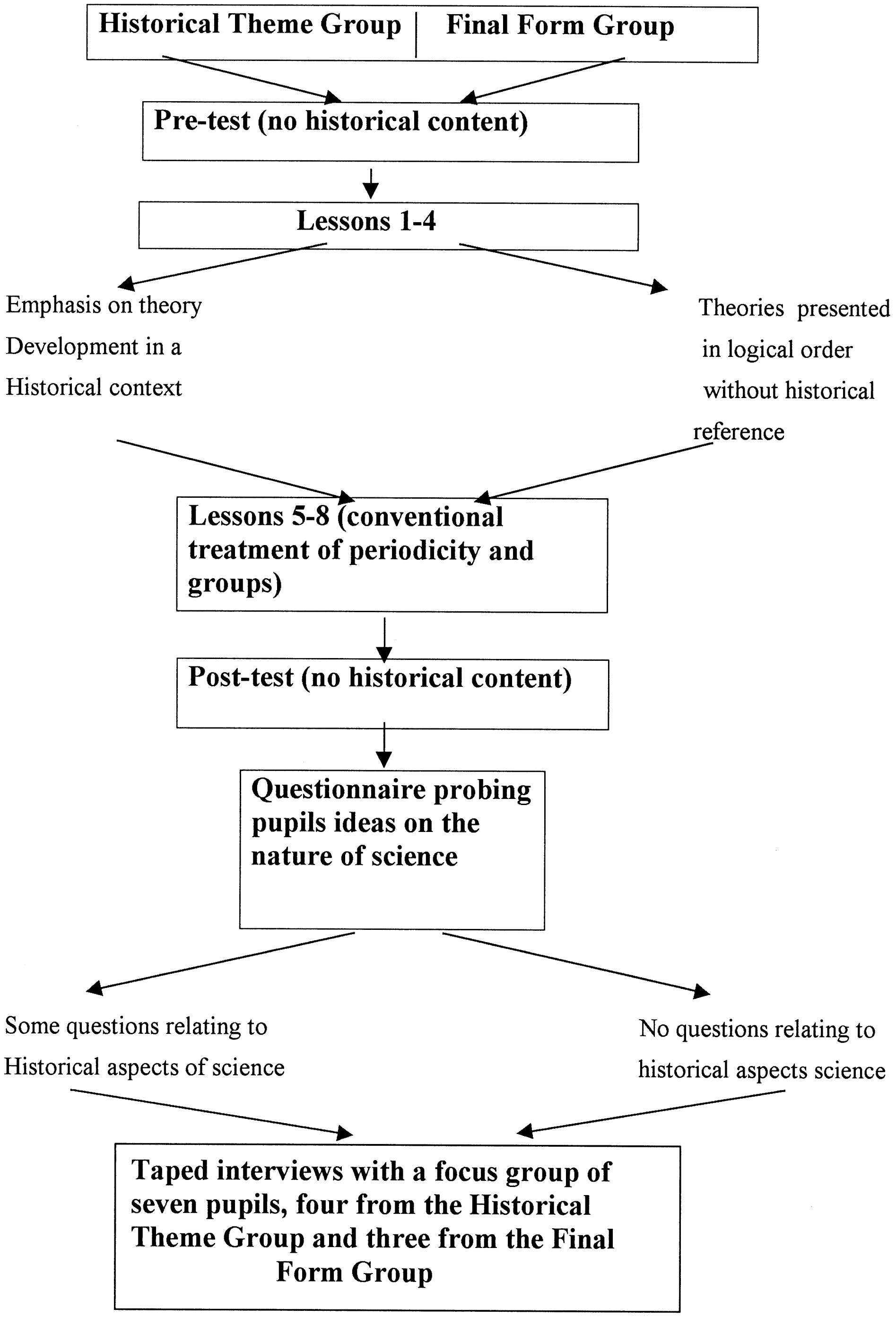

Figure 1. Format of case study.

some disappointment when these same pupils were not invited to be part of the interview group. I placated them by explaining that the purpose of the discussion was to compare and contrast pupils' views from two different angles and that their overconscientiousness had ruled them out. (Fortunately, they are well versed in the concept of a "fair test.") In the event, the FFG representatives made no substantial contribution to the discussion.

As part of the HTG unit I traced the origins of scientific thought from the natural philosophy of the Greeks. I used the article, "Empirical Foundations of Atomism in Ancient Greek Philosophy" (Sakkopoulos & Vitoratos, 1996), to describe the indirect empirical evidence used to support the fifth century B.C. theory of "atoms." The authors describe the concept of the atom as "a great creation of the human mind that gave a direct modern-like explanation of the world." They claimed that the arguments introduced in Greek atomic theory have their analogs in modern atomic theory, even though the nature of science has changed subsequently "from philosophical speculation . . . hypothetico-deductive science to science firmly anchored in material practice."

Chalmers (1998) disputed this claim and saw the Greek atomic theory as an obstacle to, rather than an anticipation of, modern science. He argued that, because the concept of the atom was "ontologically basic," the theory was a bar to the search for explanation at a deeper level. Also, the assertion that there was just one kind of matter left the motion and collision of atoms as the only source of change in nature. According to Chalmers, "this never led to a specific and adequate explanation of anything." He saw the earlier science as illustrating some features of modern science because of the significant differences between the two. Whichever opinion has greater merit, the comparison of the kinds of science being practiced in different eras is illuminating. An advantage of the Greek theory in regard to modern school science is that the everyday experiences cited in support of it, like the wearing down of stone steps by passers-by, the spreading of a scent and the orderly growth, and decay of humans, animals, and plants, are all easily recognizable by modern-day pupils.

Because the Greeks did not carry out practical experiments the evidence for atoms relied partly on thought experiments. The problem of slicing a solid cone horizontally and posing the question, "Is the upper surface exposed by the slice the same size as the lower surface?" is an intriguing puzzle for the pupils. The aim is to lead them through the same sort of reasoning that the Greeks used to reach the conclusion that if the upper surface were not at least one atom smaller in radius at the lowest possible limit then the cone would be a cylinder.

A cruder example of thought experimentation was to ask the pupils to imagine an iron nail being cut in half, followed by one of the halves being cut in half, and so on, until the stage was reached when no further division was possible. I asked the question "Is there a point where we reach a particle which is indivisible?" The purpose of the exercise was not to guide the students to the desired answer but to show them the kind of thinking the Greeks used to come up with their theory, deprived as they were of the enormous amount of technical information and instruments available to us today. The point was made that thought experiments had had a significant part to play in making scientific progress.

The difference in approach can be illustrated by my treatment of Dalton's atomic theory. For the first of these groups I described the context of his work—the fact that he was aware of the Greeks' ideas on atoms and his familiarity with the work of Robert Boyle and Isaac Newton. I gave the pupils a list of the few "elements" available to Dalton and pointed out the inadequate data on which he based his proposals (i.e., that some of his "elements" were compounds that were as yet resistant to analysis into their component parts):

HTG Lesson 3 content:

In 1807 Dalton’s list of atomic weights was restricted to 20 elements (some of which are now known to be compounds). His list of symbols and atomic weights are shown below:

HYDROGEN 1
AZOTE 5
CARBON 5
OXYGEN 7
PHOSPHORUS 9
SULPHUR 19
MAGNESIA 20
LIME 24
SODA 28
POTASH 42
STRONTIAN 46
BARYTES 68
IRON 55
ZINC 56
COPPER 56
LEAD 90
SILVER 190
GOLD 190
PLATINA 190
MERCURY 167

Tick off the names of the substances that we still regard as elements.

The second group was presented with Dalton’s statements about atoms as a cornerstone of chemical theory without any historical context:

FFG Lesson 3 content:

Our modern idea of atoms is based on Dalton’s Atomic Theory.

(i) The atoms of any one element are identical to each other and different from the atoms of any other element, especially in the weight of the atoms.
(ii) Atoms are indivisible and indestructible and cannot be created.
(iii) When atoms of different elements combine they do so in small, whole number ratios.

Because it is not possible to weigh accurately one atom of an element a more convenient idea is to compare the weight of an atom of each element. This can be done by comparing the weights of elements known to contain an equal number of atoms. As hydrogen has the lightest atom it is convenient to think of the weights of the other atoms in terms of how many times heavier they are than hydrogen:

for example, an atom of hydrogen = 1
an atom of oxygen is 16 times heavier;
.’. an atom of oxygen = 16’.

This “final form” presentation is a simplified, cleaned up version of the events. In fact, Dalton’s “rule of greatest simplicity” initially led him to the assumption that the formula of water was HO. The HTG was made aware of his mistake:

HTG lesson 3 content:

If Dalton had no idea of the numbers of atoms involved in chemical combinations he applied the rule of greatest simplicity—that is, one atom of element A combines with one atom of element B. Because he could calculate the weights of elements that combined (such as the weights of hydrogen and oxygen in water) he could work out the relative weights of the atoms:

For example, 1g hydrogen combines with 8g oxygen to give 9g water.

> One atom of oxygen is eight times the weight of one atom of hydrogen. (In this case he was wrong—two atoms of H combine with one atom of O and one atom of O is 16* heavier than one atom of H.)

In teaching the unit with a historical theme it became apparent how much better this approach lends itself to philosophical discussion. I was conscious that, in tracing historical origins back to natural philosophy, I was teaching pupils a kind of "metascience" whereby the discussions often centered on what kind of knowledge can be called "science" and what standards of justification there have been for claims of scientific knowledge. I was also conscious that the majority of pupils in both groups will join the ranks of adults we classify as nonscientists. For these pupils, in particular, I felt a responsibility to try and distinguish between the sort of scientific knowledge that is undisputed and that which is more speculative and more liable to refutation, because they are less likely to achieve that understanding when they leave school. The history of the development of the Periodic Table provides such opportunities:

> *HTG Lesson 4 content:*
> In the years up to 1870 the list of known elements and their atomic weights increased to 63. Also, a Swedish chemist named Berzelius devised a new system of symbols and produced more accurate atomic weights in 1826. This increased knowledge was accompanied by several efforts to detect a pattern among the elements.
>
> In 1866 a British chemist named John Newlands arranged the atomic weights of the known elements in increasing order and found they formed a "law of octaves" in which the first element in the series was similar to the eighth. This speculative pattern was treated with scorn by other scientists. It was discussed at a meeting of the Royal Institution where a fellow scientist asked him sarcastically if he had ever investigated the pattern formed by the elements when he sorted them into alphabetical order. Despite this crushing initial opposition, the idea was taken up by a Russian chemist called Mendeleev who decided that Newlands had tried to fill gaps with known elements when they ought to be filled by elements yet to be discovered:

Section of Mendeleev's Periodic Table:

HYDROGEN						
LITHIUM	BERYLLIUM	BORON	CARBON	NITROGEN	OXYGEN	FLUORINE
SODIUM	MAGNESIUM	ALUMINIUM	SILICON	PHOSPHORUS	SULPHUR	CHLORINE
POTASSIUM	CALCIUM	—	—	VANADIUM	—	—
COPPER	ZINC	—	—	ARSENIC	SELENIUM	BROMINE

> Mendeleev was so convinced that his Periodic Table was right that he predicted the discovery of elements in the future that would fit into the empty gaps he left in the table. Here is a comparison of his predictions for Germanium with the observed facts about the element when it was discovered.

Predictions (1871)	Observed facts (1886)
1. Relative atomic weight 72	1. Relative atomic weight 73
2. Light grey metal	2. Dark grey metal
3. Will combine with 2 atoms of oxygen to form a white powder	3. Combines with 2 atoms of oxygen to form a powder
4. The chloride will have a boiling point less than 100 deg. C	4. The chloride boils at 86.5 deg. C

> Mendeleev's classification created little interest until his prediction of missing elements and their compounds was borne out by their discovery; for example, the discovery of Germanium (Ge) by Winkler in 1886.

This episode is a clear example of the development of the germ of an idea, through to a respected but tentative theory, and henceforth into the undisputed bedrock of scientific knowledge.

RESULTS

1. Pretest

Final form group (FFG), 24 pupils—average mark 34.3%; historical theme group (HTG), 18 pupils—average mark 28.9%.

2. Posttest

FFG—average mark 36%; HTG—average mark 35.7%.

3. Questionnaire

Q1. Were atoms discovered or did somebody imagine them?

A1. FFG—all pupils answered that atoms had been discovered; HTG—8 pupils answered that atoms had been imagined.

Q2. How would you describe an atom?

A2. FFG—3 pupils said that they were indivisible—14 focused on the size of the atom, for example, "microscopic" and "one million could fit onto a full stop." HTG—13 pupils answered that atoms are indivisible, cannot be split, cannot be broken down, or cannot be cut in half.

Q3. Did Mendeleev leave gaps in his Periodic Table because he was not sure about his theory or because he was sure he was right?

A3. FFG—not applicable. HTG—13 pupils thought Mendeleev was sure he was right.

Q4. If Mendeleev found that there were some elements he could not easily fit into his pattern would he would: (i) ditch his theory; (ii) search for an explanation; (iii) accept that you can't explain everything. Tick the one you think is most reasonable.

A4. FFG—not applicable. HTG—0 chose response (i); 14 chose response (ii); and 4 chose response (iii).

Q5. Which would impress you most—a theory that explained things we already know about or a theory that predicts things yet to be discovered? Which of these is taking the bigger risk?

A5. FFG—18 pupils said that a predictive theory would impress them most. HTG—15 pupils said that a predictive theory would impress them most.

Q6. Are scientists ever wrong in their theories? Can wrong ideas in science ever be useful?

A6. FFG—1 pupil said that you could learn from your mistakes; 3 others said that the wrong idea could lead to a new idea; 3 pupils said that wrong ideas could not be helpful; 17 pupils answered "yes" without any further elaboration. HTG—12 pupils elaborated on their "yes" answers; 3 of these said that you could learn from your mistakes; 4 pupils said that the wrong idea could lead to other ideas; 1 pupil said that the wrong idea could "uncover" other ideas; 1 pupil said that a wrong idea would prevent other scientists from making the same mistake.

Q7. Do scientists make up their theories from scratch or do they get ideas from other people?

A12. FFG—7 pupils answered that scientists get their ideas from other people; 6 pupils answered that scientists make up their ideas "from scratch"; and 8 pupils answered that it was a combination of these two things. HTG—8 pupils answered that scientists get their ideas from other people; 4 pupils answered that they make up their ideas "from scratch"; and 4 pupils answered "both."

4. Focus Group Discussion (Taped)

It was interesting that the four HTG pupils dominated the discussion, partly because I asked them questions directly but also because they seemed more comfortable with the situation; that is, a philosophical discussion about the nature of scientific knowledge rather than science *per se*. There was also a practical difficulty in involving the more conscientious members of the FFG, because they had, unfortunately, ruled themselves out for reasons I have already given. I was able to identify four general results:

1. It was apparent that the HTG pupils had gained some understanding of the way in which scientific knowledge grows. They were aware of the origin of the "atom" as a model which enabled philosophers to explain some puzzling phenomena. The following is from tape transcript 1 (T = teacher):

> T: What did the Greeks say?
>
> Jason: About atoms. That you can only split things up to a certain point.
>
> T: Okay, we took an iron nail and we said you could split it in half and you keep splitting it in half until you get to what?
>
> Jason: To an atom.
>
> T: Okay, did the Greeks do any experiments?
>
> Jason: No.
>
> T: So in fact they only thought about atoms and talked about atoms. So in the first case do you think the atom was discovered or did somebody imagine it?
>
> Jason: Somebody imagined it.
>
> T: They said that you can't divide atoms but they also said that you can rearrange atoms. They said that the food that we eat makes up our bodies—our bones, our blood, our skin. So what happens to the atoms in our food?
>
> Richard: Oh! yes—you are what you eat.
>
> T: Right. So the atoms in what you eat just get rearranged inside your body.

2. The pupils were able to empathize with Dalton's lack of data and to appreciate the power of his imagination and creativity in proposing a theory based on flimsy evidence. Even the fact that Dalton's theory was wrong in some parts did not diminish its power to establish more scientific knowledge. I stressed particularly the small number of (what are currently recognized as) elements known at the time and that there were compounds that were mistakenly thought to be elements because of the lack of any suitable method of analysis. The following is from taped transcript 2:

> T: Dalton said something about atoms.
>
> Alice: He said they were indivisible and couldn't be created.
>
> T: Was he right about that? Was he right about the fact that they were indivisible?
>
> Alice: No.
>
> T: No, he wasn't right. It was in fact subsequently found out that they can be smashed up. Okay, so his ideas weren't entirely correct. Were they useful ideas? Alice, do you think they were useful.
>
> Alice: Quite useful, because they could see what he'd done wrong.
>
> T: Right. Okay, does anyone remember how many elements, from the people who did the history, how many elements did Dalton have to play with?
>
> Jason: Ten.
>
> T: No, he had twenty. But you're right, in the end he only had about ten because, was he right about some of the elements? Were they elements? What were they?
>
> Richard: They were compounds.
>
> T: Why did he think they were elements?
>
> Richard: He didn't have the equipment.

3. The discussion showed that pupils appreciated that scientific knowledge was not a static body of facts and principles but was always in a state of flux. They were aware that all scientific knowledge is open to question and that some knowledge is more questionable than others. They seemed to think that future growth in scientific knowledge will depend on advances in technology and experimentation. The following was from taped transcript 3:

> T: Mendeleev had about sixty elements to play with, slightly more than that, and he decided that Newland's idea was right. He could actually see periods in the elements. What was brilliant about Mendeleev's Periodic Table. Alice, Do you remember? What did he do?
>
> Alice: He predicted that there were elements yet to be discovered and he left spaces.
>
> T: Brilliant. Absolutely. He left gaps in his Periodic Table and in fact 11 years later one of those gaps was filled by an element which he predicted to be exactly as it was. Right. Okay, do you think that's it for the Periodic Table? Do you think there is anything left? Is there a possiblity that somebody could come up with some new idea or have we got the whole story there?
>
> Alice: There might be more.
>
> T: Do you think that in general in science what we have got now is the finished article or are we going to get more ideas, more theories coming up — or have we finished?
>
> Alice: I think we'll get more because scientists will still keep on doing experiments.

DISCUSSION

When I embarked on the unit using a historical theme it was evident that pupils were slow to accept my different approach. I noticed the same initial reluctance in a previous case study and it was, therefore, no surprise. The reason is neatly expressed in the opinions of one science teacher interviewed by Lakin and Wellington (1991):

> They don't expect reading and discussion or drama and role play—they do expect Bunsen burners and practical work. They don't want to find out that science is not a set of facts,

> that theories change and that science does not have all the answers—they want the security of a set of truths that are indisputable. They see no place for their own interpretation or theories but want to know what should happen in a particular investigation and what this proves.

I believe this is an accurate portrayal of the expectations of many secondary school pupils and I think it points to a pedagogical stance that has become ossified, making it difficult, at first, for pupils to accept a more innovative approach.

Having cleared this initial hurdle, pupils in the HTG seemed to welcome the opportunity to participate in philosophical discussion. For example, a comparison of responses to Q1 on the questionnaire shows a greater willingness by the HTG to consider the philosophical arguments relevant to the nature of science and to articulate those arguments. Philosophical reflection seemed to form an integral part of class discussions with the HTG. The response to the questionnaire by the FFG suggested that they had been "caught cold" by the philosophical questions. I deliberately stressed with the HTG that the philosophical questions were fundamental to their understanding of the subject.

The most striking result of the questionnaire was that all the pupils in the FFG believed that atoms had been discovered, whereas only 10 of the 18 pupils in the historical development group thought likewise. This result suggests that most pupils adopt the "realist" stance toward scientific knowledge. They clearly assume that atoms exist in the same way that tables and chairs exist. That the final form group should make this assumption could well be the result of my own and the textbook's inability to stress that the concept of the atom is a model; that is, it was originally an arbitrary construct that could usefully explain observed phenomena. The fact that over half the HTG should take the realist position is more disappointing given my efforts to establish the origins of the atom as an idea arising from natural philosophy. (The popularity of the realist view is supported by researchers like Solomon et al. [1994], who found that 60% of pupils preferred the realist claim that "scientists have proved by experiment that particles exist," whereas only 17.3% chose the instrumentalist response that "scientists can explain what happens by imagining how particles move.")

This result leads me to wonder how many other models in science are accepted by pupils unquestioningly as "real entities." Unless teachers place due emphasis on the process whereby these models come to be accepted then it will not be surprising if pupils (and subsequently the public) come to regard human imaginings, however widely accepted, as absolute truth. Even in Dalton's time there was debate between those who accepted that matter behaved as though it consisted of atoms and those who believed in atoms as "real" entities. Whatever the strength of more recent evidence for atoms teachers do pupils a disservice by talking about them as if they have the same ontological status as ordinary objects because this obscures the origin of the concept as a human construct, freely imagined and postulated as an explanatory theory. The wide belief during the eighteenth century in the existence of phlogiston bears testimony to the danger of a plausible model with general applicability taking on "real" existence and yet ultimately being found to be a chimera.

I am not suggesting that pupils are encouraged to adopt an extreme instrumentalist position in regard to scientific theories, merely that it is appropriate in school science to consider the status of theories. Hodson (1986) argues that both the extreme realist position and the extreme instrumentalist position have serious limitations when compared with the actual practice and history of science. He recommends a "critical realist" position as a compromise. Critical realists can be realist about some theories (which they believe to be true) and instrumentalist about others (i.e., theoretical models). He contends that use of the terms "model" and "theory" within the science curriculum, should, therefore, be an indication of the "degree of certainty" with which we hold a particular view. The historical episodes covered in this case study seem particularly suitable for making this distinction, because there are clearly traceable "degrees of certainty" attached to the developing theories.

The realist approach goes hand-in-hand with a high degree of determinism. In teaching about the construction of the Periodic Table to the HTG, I stressed the inadequacies of the table in dealing with some elements and the likelihood that, however sophisticated our technical skills became, it would never be more than an attempt to construct a pattern that would be of use to us in summarizing our knowledge and drawing generalizations. We could never look upon it as a complete description of the "truth." Most pupils in the HTG got the idea that scientists are involved in a never-ending quest for explanation but that their theories are never fully satisfactory.

On the other hand, I freely invited pupils to admire the brilliance of scientists like Newland and Mendeleev in establishing a pattern despite the realization that their information was incomplete and that "in sticking their necks out" they risked censure from their fellow scientists. I stressed that, although Newland's octaves were "far fetched," his was the kernel of an idea that was picked up by Mendeleev. With more information at hand, Mendeleev was able to see flaws in the pattern and to use a more sophisticated version of periodicity to point the way ahead for the discovery of more elements. The pupils appreciated the power and fruitfulness of Mendeleev's work in producing a theory that predated the discovery of corroborating evidence. I emphasized that, in effect, the theory had determined the evidence, in the sense that chemists searching for new elements now knew what to look for. In setting the historical context I think I conveyed my own admiration for their achievements leading to an absence of condescension from the pupils.

This episode in the development of chemical theory provided opportunities for showing that flawed theories can lead to advances in knowledge. I gave the HTG a list of the elements available to Dalton showing 20 substances, some of which are now known to be compounds. I told the group that Dalton made some highly risky assumptions such as his assumption that one atom of hydrogen combines with one atom of oxygen in the formation of water. This led to errors in calculating the relative atomic weights of other elements, which caused problems until Faraday electrolyzed water to discover that the ratio of H:O was 2:1. Nevertheless, Dalton's general assumption that the combining ratios of atoms of elements are simple was the basis on which other workers proceeded. I stressed the audacity of Dalton's contribution in adopting "the rule of greatest simplicity" when there was no empirical evidence indicating any rule at all. They could see that scientific progress had been made despite error and that the growth of knowledge is not nearly as simple as most science textbooks would have us believe.

It is important to bear in mind the fact that, for most of the pupils involved in this study, school science would be their last contact with science in a formal sense. Norris (1997) argued that one of the goals of science education ought to be to make such nonscientists "intellectually independent" of science. As defined by Aikenhead (1990) this means "to be able to assess, on one's own, the soundness of a justification proposed for a (science) knowledge claim." Norris asked "What is the nature of and extent of the critical assessment that nonscientists can make of scientific knowledge claims and of their application? To what extent can science education promote such critical assessment?" Given that nonscientists are not in a position to critically assess substantive science knowledge claims directly (in the same way in which even scientists are unable to do so in scientific fields remote from their expertise) the nonexpert should yet be able to ask and answer questions like: “Is the relevant field of inquiry sufficiently developed and sophisticated that there is reason to regard its practitioners as experts?”

The historical episode I used gave pupils in the HTG the opportunity to see the transition of a field of knowledge from a speculative idea that was greeted with derision and hostility (Newland’s octaves) into a theory that had the backing of more substantial empirical evidence (Mendeleev’s Periodic Table). The proponent of this Periodic Table had enough confidence in his convictions to make risky predictions about future discoveries, but, at this stage, there was still considerable skepticism about the whole line of thought. After the discovery of the missing elements and the confirmation of his predictions the status of the theory changed completely. There was then no longer any question of its general acceptance and all activity in the field was directed into filling in the missing parts of the puzzle.

Judging by their comments on the questionnaire and in the taped discussion it is evident that the HTG pupils were able to see, with the advantage of hindsight, how the theory of periodicity of elements had been subject to these changing degrees of doubt. I contend that they would, therefore, be in a stronger position than the FFG pupils to attempt a critical appraisal of the stage of development of a contemporary scientific field in regard to the likely certainty of knowledge and to the extent of the reliance that could be placed on the “experts.”

Time spent discussing historical contexts and philosophical questions meant that much of the practical and “contemporary” content of the HTG unit had to be squeezed into an inadequate amount of lesson time. Despite this problem there was no indication in the postunit test results of any difference in understanding, on average. Neither is it possible to say from these results that the historical perspective enables pupils to gain a firmer understanding of content, although the time factor put the HTG at a disadvantage. In retrospect, I should have allowed more time for the HTG unit. This research does show that more time spent on the historical aspects of science might well lead to a cut in conventional curriculum content, but that, in regard to pupils’ understanding of the nature of science, this time would be well spent.

APPENDIX I

Atoms and the Periodic Table—Pretest

1. Carbon, Sulfur, Iodine, Water, Copper, Gold, Salt, Oil, Carbon dioxide, Iron, Sea water, Copper sulfate

   Put the substances above under one of the headings below:
   Elements Compounds Mixtures
2. Look at the substances in Q1. Which ones are metal elements?
3. The symbols below represent atoms. Which elements are shown?
   H …………………………
   O …………………………
   Mg ……………………….
   Br ……………………….
   Fe ……………………….
   K …………………………

4. Which symbols are used for atoms of these elements?
   Nitrogen ....
   Aluminum ....
   Chlorine ....
   Zinc ....
   Lead ....
   Tin ....
5. Complete the following sentences.
   - (i) An element is a substance which ______________________________
   - (ii) A compound is a substance which ____________________________
   - (iii) An atom is ____
   - (iv) The relative atomic mass of an element is _____________________
   - (v) The Periodic Table of the elements is ________________________

APPENDIX II

Atoms and the Periodic Table—Post-Unit Test

1. Complete the following sentences:
   - (i) An element is a substance which ______________________________
   - (ii) A compound is a substance which ____________________________
   - (iii) An atom is ____
   - (iv) The relative atomic mass of an element is _____________________
2. How is the relative atomic mass used to arrange the elements in the Periodic Table?
3. In what way is the Periodic Table useful?
4. Look at the Periodic Table you have been given.
   - (i) In which part of the table are the nonmetal elements?
   - (ii) Write out the names of the elements in the group that contains Neon
   - (iii) Write out the names of the elements in the period that contains Sodium
5. Describe how Sodium reacts with water.
   How would you expect potassium to react with water?
6. The table below shows some facts about two elements, silicon and tin. The element Germanium is between Silicon and Tin in Group IV of the Periodic Table, but the information is missing. Predict what the missing information should be:

	Silicon	Germanium	Tin
Color	Shiny black	________	Silver
Relative atomic mass	28	________	119
Melting point, deg. C	1407	________	232
Conducts electricity?	No	________	Yes

7. What differences are there in the physical states of the elements Cl, Br, and I?
   What similarities are there in their behavior?

APPENDIX III

TABLE A1

Summary of Lesson Content for Lessons 1–4

Historical Theme Group	Final Form Group
Lesson 1 (a) Pretest. (b) Showing how the Greeks idea on elements developed. (c) 1661—Boyle's definition of an element as a substance that cannot be broken down by physical or chemical means. (d) Computer database search on the discovery of elements.	*Lesson 1* (a) Pretest. (b) Differences between elements, compounds, and mixtures. Definition of element as substance that cannot be broken down by physical or chemical means. (c) Computer database search on physical and chemical properties and uses of elements.
Homework—Where did the idea of the "atom" first come from and how has the theory on atoms changed?	Homework—give an account of the modern Atomic Theory.
Lesson 2 (a) Discussion of ideas arising from homework. Early Greek ideas on atoms. (b) Dalton's background and the influences on him of previous work. (c) Dalton's ideas on atoms, including where he made "mistakes"	*Lesson 2* (a) Recap on the particulate nature of matter and the concept of the atom. (b) Definition of the atom. (c) Modern atomic theory.
Lesson 3 (a) Recap on Dalton's ideas and how he acquired them. (b) Dalton's use of combining weights to calculate the relative atomic masses of elements (c) His assumption of the rule of greatest simplicity when atoms combine.	*Lesson 3* (a) Recap on three assertions of atomic theory. (b) concept of relative atomic mass of elements. (c) Building ball and stick models of simple compounds, for example, hydrogen chloride, water, ammonia, and methane.
Homework—Give an account of the historical development of the Periodic Table.	Homework—What is the Periodic Table of the elements. Why is it useful?
Lesson 4 (a) Early attempts at finding a pattern in the relative atomic masses of elements; for example, Newlands. (b) Mendeleev's improved knowledge of the elements and his early periodic table in which he left gaps, guessing correctly that some elements were yet to be discovered. (c) Mendeleev's accurate predictions of the properties of undiscovered elements and confirmation by subsequent discoveries.	*Lesson 4* (a) Use of relative atomic masses as a means of drawing up the Periodic Table. (b) Discussion of nature of elements in different areas, for example, metals and nonmetals. (c) Relationships of the elements in groups and periods. (d) Use of the Periodic Table in predicting the nature of elements using related elements.

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