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Epistemological Foundations of School Science

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Abstract. Based on a synthesis of contributions from different authors, we present a theoretical framework that provides some foundations for school science, and we define some research problems. We start from what is already known about students' models and cognition in order to construct proposals of didactical intervention. The cognitive model of science, developed in the philosophy of science through studying scientists' activity, has allowed us to propose an analogous model for school science in which experimentation and language play the key roles. We emphasise the relative independence of school science and scientists' science.

Introduction

Science education in compulsory schooling has a relatively short history, but it is rich enough already to permit a reflection upon it from different theoretical perspectives. As formal science education has been steadily increased and universalised during the last century, the questions that justify this paper have clearly taken shape: What is school science, and what are its epistemological foundations?

The analogy of the 'pupil as a scientist', centred on the experimental method as a process of knowledge *justification*, has been considered appropriate for over a century, but it may prove insufficient nowadays (Duschl et al., 1999). The current reflection on science and on science education, from the perspective of the new history and philosophy of science (NHPS) and cognitive science, challenges this analogy providing a field for research in science education. This reflection offers a new model of science that could also be appropriate for school science, provided that a 'gradual' connection can be established between theoretical models in science and students' mental representations of natural phenomena.

According to many authors (Duschl, 1990, 1998; Ohlsson, 1992; Kuhn, 1993; Solomon et al., 1994; Newton et al., 1999; Osborne, 1999) scientific education should promote a new way of theoretical thinking and of reasoning, that is, should have an important *epistemological* component. Scientific contents that are learnt at school, from the very introductory levels of compulsory education, should be *reasonable* and *reasoned*, and should participate in a system of ideas and actions that is coherent, valid, and at the reach of students. A school science with these characteristics should allow students to adequately explain some of the relevant natural phenomena that they need to understand in order to live in today's society. Only with such epistemological foundations can science education be truly apt for a general *liberal* education, and this component – which gives value to school science – should be carefully investigated (Ohlsson, 1992; Bereiter, 1994; Cobb, 1994; Driver et al., 1994).

The present paper sketches some recent epistemological models and uses them with the aim of increasing the efficiency of pedagogical interventions in the science classroom that are directed towards giving students valid criteria to act in a *metacognitive* (i.e., conscious and autonomous) way. It is a theoretical paper related to current research in schools and to science curriculum development.

Our argumentation uses Ronald Giere's (1988) model based view of science, the *cognitive model*, in order to establish a connection between scientists' science and what we call school science. To do this, we draw an analogy between models as non-linguistic entities in the realms of science *and* of students' cognition. Such connection may go beyond Giere's strictly philosophical account but is suggested in his extensive use of cognitive psychology (Giere, 1996). We also resort to some other models from the NHPS that are not strict antecedents of Giere's work but can be seen as a coherent setting for his ideas.

The Need for a New Model of Science in Science Education

There is at present an increasing agreement in reference to some of the most important theoretical concepts of science education as a discipline (Joshua and Dupin, 1993; Gil-Pérez, 1996; Adúriz-Bravo, 1999; Izquierdo et al., 1999; Lijnse, 2000). Among these, we can select:

1. the importance of *metacognitive processes*, related to the goal of helping students to think in an autonomous way;
2. the importance of *students' conceptions*, related to the goal of teaching them how to think theoretically (Duschl, 1990); and
3. *didactical transposition*, that is, the idea that science is profoundly reconstructed in order to be taught (Chevallard, 1990; Joshua and Dupin, 1993; Ogborn et al., 1996).

Simultaneously, we accept the fact that teachers' models of science influence their pedagogical models (McComas, 1998). The NHPS has strongly influenced teachers and a more *contextual* model of science is at present very frequent in science classes (Koulaidis and Ogborn, 1995), though dogmatic or empiricist views of science are still to be found. The role of the sociology of science has been important in forging this change, but radical socio-constructivism derived from it has proved to be dangerous because of its sceptical and relativistic conception of knowledge, which is unsuitable for school science. Therefore, it has become necessary to strike a balance between cognitive and social aspects in constructing a sound image of science for education.

A model of science from radical sociology that over-emphasises the role of context cannot help teachers sufficiently in their work, because although it examines the importance of creativity, discussion, and social milieu in constructing science, it fails to consider that, in science classes, we also have to incorporate references to the intrinsic importance of scientific concepts and their connection to natural phenomena. We need a model adapted to a new *cognitive* context, and therefore the analogy of the 'pupil as a scientist' has to modify its sense. If the most important element in science education is that students acquire a system of ideas that is *meaningful* from the very first moments, an initial stage of introduction to scientific culture is needed. Before students can 'act as scientists', they need a *school science* that is appropriate in order to reason starting from it.

In addition, regarding the increasing importance that is given to *argumentation* and *explanation* in science education (Duschl, 1990, 1995, 1998; Lemke, 1990; Newton et al., 1999; Osborne, 1999; Sardà and Sanmartí, 2000), we need a model that gives major relevance to the discursive and rhetorical aspects of scientific activity in the classroom.

The new orientations of the history and philosophy of science have brought theoretical reflection upon science closer to other empirical disciplines, including it in an interdisciplinary area broadly called *cognitive science*. Within this new area, models of scientific knowledge are elaborated that can be related to models of other kinds of knowledge. A cognitive model of science related to a *semantic* (i.e., representational) conception of theories is currently emerging (Giere, 1988, 1992; Suppe, 1989; Kitcher, 1993).

The so-called *cognitive model of science* from contemporary philosophy of science portrays science as a human enterprise whose aim is to interpret the world by using human capacities of thinking theoretically and progressing towards a goal (Newton-Smith, 1981; Giere, 1988, 1992). As we will see, this model could explain both scientists' science and school science in spite of the big differences between them, because the *cognitive* goal is a central feature for both. Both sciences propose the understanding of the world and the communication of theoretical ideas with accuracy and in a meaningful way.

But we must also take into account the important differences between these two sciences, for instance, the range of cognitive skills and the balance between *doing* and *understanding* that are required in each of the two. School science must then be carefully planned to conform to some extent to scientists' science; this is the central feature of the concept of didactical transposition (Chevallard, 1990; Joshua and Dupin, 1993) that we use.

We are going to analyse which characteristics of school science make it different from scientists' science and how the cognitive model helps us to understand such differences and bring the two sciences closer to one another. We will see that this cognitive model of science offers us a way to progress in the three aspects mentioned at the beginning of this section as key concepts in science education. Finally, we will show that school science can be reconstructed according to the cognitive model of science, as it has already been done with scientists' science in other studies (e.g., Giere, 1992; Nersessian, 1992).

The New History and Philosophy of Science

We will very briefly consider some of the changes in the understanding of the nature of scientific knowledge which have occurred in the last forty years, and which have very positively influenced science teaching (Cleminson, 1990; Izquierdo, 1995). We will start with a short account of the philosophy of science in the twentieth century that is suitable for our purposes.

After the *demise* of logical positivism (Suppe, 1989), the hope for an exact language in science, based on the possibility of clearly differentiating the so-called *observational* terms – those coming from experimentation – and *theoretical* terms – those related to the formal structure of the theory – disappeared; a language which did not continually escape from strict experimental and inductive definition was found to be impossible. The study of *pragmatics* showed that scientific language must be regarded as more imprecise, changing and adaptable than it had been thought before.

The conviction was stated that it was impossible to experiment without a theory, because theories are previous to experimentation and both experimentation and observational terms are *theory-laden* (Hanson, 1971). A growing interest in the history of science demonstrated the non-linearity of scientific progress and focussed on the existence of *revolutions*, which were great discontinuities in paradigms that had to be explained by the confluence of diverse internal and external causes (Kuhn, 1962). These abrupt changes modified the meaning of experimental data to such an extent that they could even impede dialogue between rival groups of scientists. If data were of little use to confirm theories, science was in danger of becoming an irrational venture (Feyerabend, 1975), a statement that contradicted what scientists believed about their own enterprise.

Therefore it was necessary to reach a less radical conclusion. In Lakatos's (1971) and Laudan's (1978) work, the history and, to a certain extent, the sociology of science are used to construct more adequate models of scientific *growth*. This fact has extraordinarily enriched the reflection about the so-called *context of discovery*. Due to the complexity of this context, philosophers of science had paid little attention to it, and the context of justification was the focus of inquiry of earlier studies instead. Nevertheless, Lakatos's and Laudan's proposals were still bound to a model of hard scientific rationality and were partly criticised for not integrating an element of abductive (i.e., creative) reasoning. More recent proposals are placed within the framework of a *moderate* rationality. In this view, having a goal – *interpreting* the world and *intervening* on it – and progressing towards this goal through decision making are the most important characteristics of any rational human activity (Newton-Smith, 1981; Chalmers, 1982; Giere, 1996).

A COGNITIVE MODEL OF SCIENCE

The cognitive model of science focuses on how scientists work and communicate (especially through writing), and highlights the semantic aspect of theories: their goal is not to reach truth but to make sense of the world, according to the ultimate objective of an active *transformation* of nature (Hacking, 1983). In this process of giving meaning, cognitive and social factors have a key role (Nersessian, 1992).

According to some other models proposed by the NHPS, there is not a unique, well-characterised scientific method, because validation criteria change through time in response to the problems to be investigated. Classical stages of experimentation – formulation of hypotheses, laws and theories – cannot be seen in a hierarchical order, either. Theories are the most important entities in science; they are constructed and modified in order to interpret the world (Duschl, 1990). The cultural environment and the characteristics of the social group in which theories are elaborated and discussed influence their own goals and the view of the world they provide. Theories do not need to be axiomatically formulated, and can be to some extent identifiable with *analogies* (Hesse, 1966; Giere, 1988, 1999). Theories and experimentation are mutually justifiable according to a *moderate* realism, in which pragmatic considerations play a key role (Pickering, 1989; Giere, 1999).

This view of science is particularly useful to study the new context of theory development and assessment, which is now emerging (Echeverría, 1995). Its results seem to be the most adequate for the science classroom, especially because of the new conception of scientific theories that this view puts forward, i.e., the semantic model, which looks for the *meaning* and *communication* of theories and for the relationships between models and the real world.

Hesse (1966) states that scientific models allow a theory to be predictive. According to Carey (1992) and Nersessian (1992), models are a kind of mental representations; the propositional language that defines a theory is not then used to *describe* the world but to construct a mental model of it, which is a structural analogue of the real situation. The interpretation of a fact may be a consequence of having related it to similar or analogous facts, which already make sense to scientists. The initial model thus generated will develop as it explains other known or new phenomena. Contributions from all these authors somehow support our proposal of seeing a school theoretical model as a *theoretically interpreted paradigmatic fact*. We will revise this idea below.

A contribution from the philosophy of science that we consider extremely suitable for our purposes is that of Ronald Giere (1988, 1992, 1999) – specifically centred on the relationship between theories and the facts they refer to. In his work, he stresses the importance of *theoretical models* in science; these models are considered a kind of mental representations similar to internal maps of the outside world. Giere (1988) considers that theoretical models can be of a very diverse nature: linguistic entities, material models, maps, analogies; almost any symbolic system can be used as a theoretical model provided that it can connect to reality through theoretical hypotheses.

The relationship between theoretical models and reality is that of *similarity*, not of correspondence or of convention as was stated in classical epistemologies. It is also through similarity that scientific theories are presented in textbooks: as a set of models related to some facts and to some identifiable instruments, which give meaning to the theory. Relationships between models and facts are developed through *theoretical hypotheses*, which can be more or less true or false, because they have empirical content. A scientific theory is then a *family* of models, together with a set of hypotheses that establish the similarity of these models to the real world. Thus, the theory necessarily contains its applications, or *domain*, and it can be understood in part as the interpreted world (Giere, 1988; Suppe, 1989).

The cognitive model of science focuses on how scientists do science, as an effective goal-directed activity. Within this framework, it is not necessary to have a previous normative definition of rationality; we talk about a *hypothetical rationality* (Giere, 1988, 1996). The question now is to characterise which effective strategies are used by scientists when pursuing scientific goals, and how they decide which models – selected among the available – are the most appropriate for those goals. With this, epistemology is *naturalised*, in the sense that it is no longer identified *a priori* with a particular way of reasoning. The cognitive approach to the study of science provides a basis for fruitful relationships between the history and philosophy of science, cognitive psychology and science education, as it proposes a very robust model of decision making in theory assessment that is not strictly Bayesian but *natural* (Giere, 1999). We believe that such a version of naturalism avoids the pitfalls of psychologism and respects scientists' views on their own activity (Siegel, 1993).

Teaching and learning science may be regarded as another aspect of developing and understanding scientific knowledge (Echeverría, 1995), hence our decision to talk about school science as a science of its own. It is then important to ensure that school science is properly founded. If the aim of teaching science is to teach how to think with theories, as well as to understand the world, the first question to be answered is what school theories must be like within this semantic conception. The cognitive model of science offers us a way to answer this question at a general level, as it denies the belief, frequent in our science classes, that the true scientific account of the world is provided by a particular formulation of a theory, generally thought to be the most abstract and mathematically sophisticated. Such a belief has been shown to be an obstacle against meaningful science learning.

On the other hand, the cognitive model of science states that a theory has as its main function allowing people to understand the world, and not the formulation of truths that are valid *per se*. If a theory fails to attain the former goal, it has little value in science education, both for students (who cannot come to understand the nature of science), and for teachers. Therefore, an important element in science education will be having appropriate theoretical models in order to make sense of those phenomena that secondary students can know and manipulate. These models should complement or substitute, but not contradict, those that have been collected in textbooks during the long tradition of teaching science to those who would become scientists.

The cognitive model of science also shows that facts of the world are heavily *reconstructed* in the framework of theoretical models: they interact between each other, with the mediation of actions, instruments and representations. Scientific language can also be regarded as instrument and action, as suggested by Wittgenstein's concept of *language games* (Izquierdo, 1995).

From our viewpoint, the cognitive model of science permits to generate proposals for school science that are coherent with the aim of teaching students how to think as scientists (that is, using theoretical models) in compulsory science education.

How a Cognitive Model of Science Works in the Classroom

For students, the study of science is to some extent compulsory. School science is then immersed in a rhetoric of authority, in which the teacher's role of *convincing* is essential (Groisman et al., 1991). This aspect has direct influence on the activities directed towards learning science at school, and strongly differentiates school science from scientists' science: scientists choose the problems that interest them, create their own theoretical models and their own language. We must admit that this is not completely possible in school science, although for a long time it was supposed that the best students were able to share without difficulties the new viewpoints that science provided.

In the first section, we will highlight the importance of goals in order to give meaning to scientific activity; this will bring us to the need that the goals of school science be compatible with those of general education, and that students be able to incorporate them. In the second section, we will see the difficulties that appear when teaching how to reason scientifically once accepted the previous limitation, and how science classroom activity can be re-oriented in order to overcome those difficulties. We organise our account in three sub-sections that correspond to the three main theoretical concepts of science education that we have selected: the role of metacognitive processes in providing goals and enhancing students' learning autonomy; students' representations of the world as a starting point for their reasoning; and the mechanisms of didactical transposition in the school science curriculum in order to create problems on which students can reason through models. Finally, in the third section, we will show how the cognitive model of science offers a theoretical perspective in order to provide the foundations for school science, so that this represents, for students, an authentic initiation into scientific thinking.

THE MAIN CHARACTERISTIC OF A RATIONAL ACTIVITY: ITS GOAL

School science needs different objectives connected to the values transmitted at school, and related to other disciplines such as social sciences and philosophy (Götschl, 1990). School science should integrate its own values with those of health, consumer and environmental education, and education for peace. Otherwise, how can we present science to students as an interesting and valuable subject whose contents generate an understanding of the world? School science has to be formulated in a global and rather utopian framework, which is always present, in one way or other, in liberal education. Unfortunately, scientific goals have become the solving of partial problems, research has been turned into a technical process more related to very sophisticated technology than to the creation of scientific knowledge that aims for a better understanding of the world (Maxwell, 1992).

What may give value to school science is having goals that students may call their own, which may conform to their expectations and beliefs about school and about the 'real world', while being coherent with the science curriculum. One of the main goals for scientists is building new knowledge; school science is different from that science of scientists, because achieving its own main goal should mean that the student is able to explain the world (its facts and phenomena) through *existing* scientific theories. Hence, the teacher as a specialist has to carefully plan school science so that it may become something intelligible in itself and not only imposed from outside.

DIFFICULTIES THAT APPEAR

Science teachers should plan interventions in the classroom in a way that these interventions are coherent, at the same time, with the three main concepts that we have developed and the cognitive model of school science.

The Importance of Metacognitive Processes: Helping Students to Think

Students need to have a suitable goal in the science classroom: only if this is the case, will all the activities make sense, and we will consider that students work and think in an autonomous way. At school, the imposed goal is to learn, but only if students accept such a goal, will learning be a cognitive activity that makes sense. This can be achieved by triggering high order metacognitive processes that permit them to assess what they are doing. Self-regulation should then be part of the process of learning, within the so-called *didactical contract* (Jorba and Sanmartí, 1995) that regulates life in the science classroom. Students can thus perceive that they are responsible for the construction of their own knowledge, and in this context the cognitive model of science becomes valid for school science. According to these ideas, we need *dynamic knowledge* in the science classroom (Perkins, 1986), that is, knowledge that can be applied and responds to meaningful questions.

The Importance of Student's Ideas

Students' ideas about natural phenomena provide us with the first anchoring models that can be considered in the classroom (Clement, 1993). But it is necessary to relate the new scientific knowledge – formulated through another kind of models, those described by Giere (1996) – to children's own ideas *about* knowledge. As we have said, we are looking for dynamic knowledge in science, and would try to associate this with the philosophy of science, according to the epistemological objective of teaching how to think. Such a cognitive aim for school science may provide the bridge with Giere's account of scientific activity.

The teaching of sciences reconstructs them to make them comprehensible to students who, if the process is successful, will then have criteria about which knowledge is valid, and why it is so (Joshua and Dupin, 1993). Science teachers have a great deal of freedom in the classroom; one of their functions is to design activities that make students think and act upon certain natural phenomena. It would then be useful to offer a kind of *school scientific theories* in the classroom that may connect children's ideas with new experimental facts presented to them (Duschl, 1995). These school scientific theories should be different in content and in language from those of scientists', but retaining a similar power of explanation; they should be capable of evolving to correlate, in the future, more experimental facts expressed in a more abstract language.

Didactical Transposition

As a result of science education, students should understand that the natural world presents certain characteristics that can be theoretically modelled. Because of this, we are going to present to them some reconstructed facts, theoretical models, argumentations and propositions that we have previously selected. Teachers are professionally committed to teaching the science of today *as if it were true*. Obviously, this is not 'doing science' but 'teaching science', and the justification for this behaviour is to be found in *didactics* of science and not solely in science. Scientists propose theories and methods to achieve their own explanatory aims, but this is not entirely possible for students at school.

Besides, if work in the science classroom is carried out according to the principles of a well-performed didactical transposition (Chevallard, 1990), teachers are also professionally committed to connect scientific models to those used by students themselves, resorting to the analogies and metaphors which would best help them to move from the latter to the former (Duit, 1991; Flick, 1991; Ingham, 1991; Clement, 1993). Throughout school years, this should result in a process of selecting the relevant questions suggested by experiments and the contexts in which these questions make sense to students. Although not all questions will always be answered in class, they can be discussed there: some of them bear a philosophical, historical or social reflection; some state ethical, social or juridical problems; others refer to non-scientific beliefs which may be compatible with science because they go beyond the problems that science addresses. Perhaps teachers should give priority to those characteristics of theoretical models that are present in all school disciplines and subjects.

Learning science at school cannot entirely be compared to solving new problems with a strong scientific background (the analogy of the 'pupil as a scientist'). But, at the same time, we are convinced that we reach different stages in acquiring scientific knowledge; there should be no great discontinuities in the process. If the main feature of science is theoretical thought that allows the interpretation of the world, this is what scientists' science and school science must have in common. This fundamentally cognitive element permits the connection between the two sciences.

RECONSTRUCTION OF SCHOOL SCIENCE WITH THE HELP OF A COGNITIVE MODEL OF SCIENCE

The cognitive model of science pictures theories in a flexible and evolutionary way and does not rigidly condition them to the pattern of a scientific method that is impossible to reconstruct in the classroom. Using this model, we can establish a bridge between the two sciences and, on doing so, we are allowed to focus on the real points of agreement between science and science education, which is what we, as science teachers, are looking for.

We have seen that within current theoretical frameworks science education is easily compatible with a cognitive model of science; it is possible for students to take construction of their knowledge as their main objective, and it is possible for teachers to provide them with theoretical models that they can use meaningfully, as long as school science is carefully planned. We know that science at school cannot be the re-discovery of scientific theories, nor an imitation of the scientific method; but we cannot teach science with the message that we are not able to know the world because theories change or because there are many possible valid approaches. Neither can we restrict ourselves to teaching the nature of science without teaching how the constructs of science work in explaining the world. At school, science has a *normative* component that should be as far as possible made compatible with students' autonomy provided that that component is not distorted. But compatibility requires new didactical and epistemological approaches.

No matter how different scientists' science and school science may seem, we must not forget that the latter can be regarded as an important part of the development of the former: the history of science shows us that what science is and what it will be depends largely on what is *taught* about it (Nye, 1993; Izquierdo, 1995). Therefore, if suitably planned, it is possible that science teaching in a value-laden framework could be similar to the construction of science. It is possible only if we accept that trying to explain the world theoretically is the most important characteristic of science, *and* the major objective for school science. With this restriction, school science becomes a meaningful activity for students, and it offers a kind of knowledge about the world that is also epistemologically founded.

The cognitive model of science and the semantic model of scientific theories lead to a school science which presents theoretical models to interpret the world, and which makes them develop in a reasonable way as new phenomena appear and need to be interpreted. Thus, the level of abstraction that language (natural, mathematical or symbolic) can have in the science classroom without losing its communicative power is decided within the framework of a pragmatic realism. The cognitive and semantic models show that the understanding of the world guided by *cognitive* objectives is crucial, and that any theory that lacks this element has little value for students. These models also show that it is possible to decide about the validity of knowledge thanks to socially shared goals about performance in the world.

Two aspects emerge now: experimentation and language. Their role in the science classroom has to be reconsidered (Izquierdo, 1995). These two aspects can be related to an important element of school science: the *paradigmatic fact*, which we will briefly develop here. The theoretical and linguistic construction of paradigmatic facts in the classroom may be considered one of the major objectives of school science (di Sessa, 1983; Izquierdo & Márquez, 1993). As a consequence of this idea, new theoretical problems appear, generating new fields for research.

Proposals for Research in Science Education

The theoretical construction of a scientific fact is impelled by a wish to understand, to construct mental and discursive tools, to communicate ideas, and to be able to *intervene* on the world.

One of the principal problems in science education is achieving that students use the scientific entities introduced in the science classes in order to intervene on the world with their own ideas and actions. Therefore, we should select some relevant facts and deeply work with them in order to reconstruct them in the classroom within the framework of a theoretical model, so that these facts become paradigmatic facts that contribute to the development of that model.

A fact reconstructed by means of a theoretical model next to students' mental models is more likely to have meaning for them. Thus, facts validate the model, but the model gives value and meaning to facts, which are *only* understood due to such model. Pragmatic realism shaped in this way escapes relativist or extreme instrumentalist positions, which deny that scientific theories say something about the real world (Giere, 1999).

EXPERIMENTATION

Experimentation cannot have the same place in school science as in the science of scientists, nor the same epistemological value. Scientists consider that scientific knowledge is strongly experimental and, indeed, the structure of research articles gives an outstanding place to the experimental component, transforming it into one of the most important rhetorical resources of conviction. In opposition to this, it has been repeatedly stated that very few students take real advantage of laboratory practice to construct theoretical knowledge (Hodson, 1992, 1994).

Scientific experiments must be reconstructed in writing (Kuhn, 1993), and so it is necessary to teach students how to write science (Lemke, 1990).

WRITING

A good explanation for students should be based on a coherent relationship between action, instrument and theoretical model (Pickering, 1989); the latter may simply be a metaphor or an analogy. A theory completely expressed in the language of scientists, not connecting with what students can do or with the phenomena they have access to, has no value for them: it is an empty formalism, and it would be a mistake to teach students to appreciate it only because it is supposedly scientific.

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 (Nye, 1993). In order to give momentum to this process, it is necessary that students learn how to use argumentation in their discourse (Duschl, 1998; Sardà and Sanmartí, 2000).

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. Causal reasoning is in fact responsible for almost all the arguments constructed in the science classroom; we then realise that it is necessary to promote oral and written discourse in the classroom that enhances the use of reasoning.

According to the rules of discourse, a *solid* argument has to be valid, suitable and complete; in science, it also has to correspond to experimental conclusions. But it is not easy to accomplish these requirements. In science, the extent of certainty is always dependent on the validity of a particular theory through which the results of the experiments are analysed. For the same reason, arguments are never complete, as all the aspects of a phenomenon that do not correspond to the underlying theoretical model are left aside. But this does not prevent arguments from being (pragmatically) *adequate* to the objectives they pursue; and this is also true in school science (Osborne, 1999). In this way, argumentative abilities, and the outcomes of these, are developed at the same time as the theoretical models.

A model of explanation suitable for school science is the *illocutionary* model of scientific explanation, according to which attention is paid both to the structure of the explanation and to its results (Achinstein, 1968). In this way, we avoid disconnection between what students think and do. For us, a good explanation in school science is one that gives an answer to a question within a school science context, which is correctly written, which uses the strongest possible theoretical model, which is understood by students, and which permits them to act empirically.

In order to implicate students in classroom discourse, questions are asked in diverse situations and also with diverse intentions: a problem we must solve, something we cannot explain, a complex fact that we wish to narrate either orally or in writing, some actions we wish to perform. In each case we can generate a sequence of questions and answers that can contribute to the construction of applicable knowledge (Perkins, 1986). Therefore, our sequence has:

1. What we already know and what we are looking for.
2. The theoretical model, which is a representation of the phenomenon and of our actions upon it.
3. The analogical relationship with other empirical situations that are known and which correspond to the same conceptual and procedural structure, and contribute to the robustness of the model.
4. The arguments that associate facts, procedures, symbols and ideas through reasoning and discourse.

RESEARCH QUESTIONS

Based on the synthesis that we have presented, with contributions from different authors, and according to our theoretical framework, we may now define some research problems (Izquierdo, 1995).

In science classes the most suitable questions are those that favour the development of theoretical models similar to those in scientists' science *but* adapted to school experimentation and language. From this perspective, the facts in everyday life can be discussed through school theoretical models that will develop progressively towards those held by scientists. But the structuring of school science needs an adapted version of Ockham's razor to work in the classroom: very few models and facts should be presented, but the most robust and inclusive ones should be selected. Without this restriction, the whole process of asking questions can become dispersed and therefore sterile.

Our proposal generates the following research questions:

1. Which could be the *paradigmatic* facts for school science?
2. Which are the suitable theoretical models? How do they develop? What is their relationship with these paradigmatic facts?
3. Which proposals enhance students' independent analysis of models, phenomena, actions and instruments?

4. How should we plan teaching interventions to favour students' self-regulation within this context?
5. How does language contribute to the shaping of paradigmatic facts and thus to the learning of science?

It is reasonable to believe that the cognitive model of school science that we have briefly sketched above may well provide some theoretical guidelines in order to address these research questions.

Conclusions

The cognitive model of science that contemporary philosophy has developed by studying scientists' *activity* has permitted us to propose a model for school science in which experimentation and especially language play the key roles in the construction of school theoretical models. These two activities transform students' world of phenomena into the world-on-paper of science without breaking the continuity between them both. This is coherent with a metacognitive approach to science learning that is favoured in current research in science education. We believe that the acceptance that theoretical thought (i.e., thinking through models) is the most important feature of science, may represent a significant advance in our teaching proposals.

We have emphasised the relative independence of school science with scientists' science. From the teachers' point of view, the justification of school science (objectives, contents, instructional strategies, sequencing) is provided by didactics of science (science education as a discipline). In this paper we have been interested in exploring the characteristics of school science that may turn science into valid and meaningful knowledge for students. This knowledge consists of relevant facts about the natural world, which are related to values; such values impel cognitive activities, which need a goal. With all this in mind, we have tried to picture science teaching as an activity that helps students acquire rigorous and comprehensive models about the world and, at the same time, develop autonomous thinking that enhances their future learning.

The key problem that we have met is how to respect, at the same time, the dynamic and constructive nature of learning and the normative nature of science; science teachers believe that the world functions in a certain way (which is what the students *must* learn) and not in another. In our proposal, this contradiction can be solved by increasing the autonomy of school science, in such a way that school theoretical models are adjusted to students' world and therefore have a meaning for them, while retaining as final target the accepted scientific knowledge.

If school scientific models do not clash with analogies and metaphors, but on the contrary agree with them, school scientific language acquires the necessary depth to make it an instrument of communication and understanding. At the antipodes of this proposal we usually find a school science that imposes void scientific theories with no relationship to phenomena out of textbooks and stuffed of over-precise scientific language, which is to be learnt by rote.

What interests us is to present school science in such a way that it is closer to dynamic knowledge about the world, rather than to a sophisticated and obscure technology. For this reason, we think that reflection and self-regulation should be empowered. An effort should be made to centre science teaching on broad thematic fields, and theoretical models should be simplified to a maximum, always trying to make use of powerful concepts that comprise experimental and theoretical meanings.

The use of a cognitive model of science for school science gives our proposal new aspects that could be carefully investigated. Once the limits of school science are accepted (it has to present some particular models of the world, and not others), we delimit a wide space of freedom for science teachers. Teachers are allowed to explore which relationships between theoretical models and phenomena, and between both of them and language, are the ones that may best be developed in the classroom. Experiments and language in school science do not need to be strictly those of scientists for students to reach meaningful scientific knowledge. Science teachers should then be free to organise teaching without trying to imitate scientists' methods and objectives: the questions and the answers considered in the classroom will be different from those of scientists, and still profoundly connected to them.

At present teachers can already perform this complex process of recreating scientists' science in the classroom, according to their own values, institutional conditions, rhetorical tools, and educational objectives, to convert it into school science. If we agree to call this process *didactical transposition*, such concept becomes fundamental in science education and coalesces around itself other well-known constructs, becoming an important theoretical nucleus for our discipline.

The aim of this paper has been to sketch a theoretical framework for school science incorporating contributions from current philosophy of science and didactics of science.

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