Designing Courses on the Nature and History of Science

11

Designing Courses on the Nature and History of Science

Bernard Leyh, Gustavo Avitabile, Orla Kelly

Although science is ubiquitous in all our lives, we often fail to appreciate that doing science is not simply a matter of reading and understanding textbooks or implementing high technology applications. Doing science involves a complex network of human activities which includes the highly debated domain of validity and its associated limitations. The education of responsible future citizens requires that they become knowledgeable not only about scientific content but also about what science actually is and the nature of scientific thinking and reasoning. This requires in turn an appropriate education for future secondary school science teachers. The following chapter aims to provide pre-service teacher instructors (i) with a theoretical, research-based framework, dealing with teaching approaches and curriculum definition, and (ii) with detailed information on a practice-based approach which has been developed and assessed at the University of Liège (Belgium) for several years. A brief discussion on the role of history of science in this context is also included.

Introduction: why it is essential to teach about the Nature of Science

Developing scientific literacy is more and more recognized as an essential goal of secondary school education (Further Reading: McComas et al., 1998) (American Association for the Advancement of Science, 1989, 1993; Matthews, 1994; National Research Council, 1996; Kremer & Mayer, 2013)[1].

> Scientific literacy is usually considered to involve two independent aspects: (i) a reasonable knowledge and understanding of the most important ideas of contemporary science, in particular those which are pertinent issues for society; (ii) an understanding of what is generally called the Nature of Science (NoS) and which encompasses epistemological issues (What is the scientific world view? What are the characteristics of scientific knowledge? Where are its limits? What distinguishes science from non-science?) as well as procedural aspects (How is scientific knowledge gained? How does scientific inquiry take place?).

These ideas will be further developed in the Theoretical Framework part. In other words, scientific literacy is not simply knowledge of science but also – and many would say, more importantly – knowledge about science. McComas et al. (Further Reading: 1998) emphasize clearly the importance of a sound NoS understanding in general education: "… few individuals even have an elementary understanding how the scientific enterprise operates. This lack of understanding is potentially harmful, particularly in societies where citizens have a voice in science funding decisions, evaluating policy matters and weighing

[1] The bibliography has been organized into two parts. In the "Further Reading" section, we selected a limited numbers of books and review articles on the Nature of Science, on its teaching and assessment and on the history of science. Reference to these works in the text is preceded by the mention: "Further Reading". The other research articles referred to in the text are listed in the final Reference Section.

scientific evidence provided in legal proceedings. At the foundation of many illogical decisions and unreasonable positions are misunderstandings of the character of science." (p. 511)

This latter citation highlights an essential aspect of scientific literacy: understanding the relationships between science and society and the importance of scientific issues in often complex societal decision-making where many different and partly conflicting aspects, including ethical questions, must be considered. Funtowicz and Ravetz (1994) coined the term "post-normal science" to refer to such situations "where system uncertainties and/or decision stakes (or both) are high". To clarify these different aspects of scientific literacy, Roberts (2007) distinguishes between what he calls vision I and vision II (see also Dillon (2009)). **Vision I** focuses on science itself, both on its procedural aspects and on its products (laws, models, theories). This corresponds broadly to the definition of NoS that we proposed in the previous paragraph. **Vision II** concentrates more on the societal role of science, in particular for decision-making, and therefore overlaps with the concept of post-normal science. We will examine later how to include science-to-society links into a NoS curriculum.

The previous introductory considerations imply that school students should become aware of NoS through various school activities. This pedagogical tendency is not new and dates back at least to Dewey who advocated the importance of understanding how science develops in 1916 (Further Reading: McComas et al., 1998). Key developments occurred in the 1960s but the major impetus came in the 1980s and 1990s, as illustrated by Matthews' book *Science teaching. The role of History and Philosophy of Science* (Matthews, 1994), and also by calls from scientific associations like the American Association for the Advancement of Science (1989, 1993) and the National Research Council (1996). This pedagogical evolution is paralleled by a development of the associated research focused on NoS. A bibliographic survey using SciFinder shows a steady increase in the rate of research publications involving epistemological issues, proving that reflecting upon NoS is of increasing concern and interest.

This evolution must be considered in a more general frame. All over the world, a general tendency is observed in secondary school education to move from a teacher-centred to a student-centred approach. This is evident in science where the development of scientific competencies and promotion of scientific attitudes play a more and more significant role. School students are then expected to learn – at least partly – by engaging with and solving specific scientific problems or tasks, using an inquiry-based scientific approach. Whether this can be attributed to policy, best practice in science education or to requests from employers' for more skills to be developed in secondary school remains an open and debated question.

Developing a sound scientific approach in the classroom together with critical thinking therefore requires future teachers – and, through them, hopefully school students – to be aware of the ways in which scientific knowledge is built. The epistemologies of the different scientific fields, such as chemistry, physics, biology and earth sciences, display specific aspects which have to be addressed in order to guide secondary school students in their efforts to solve a given task. For example scientific modelling has acquired an ever increasing importance in student-centred education so that the use, the role and the status of models need to be well understood by both teachers and school students (Van Driel & Verloop, 1999; Justi & Gilbert, 2000; Justi & Gilbert, 2003; Gilbert, 2004; Treagust et al., 2004; Prins et al., 2008; Pluta et al., 2011).

Given these arguments, it is then clear that science teachers need to have reflected upon how their field has developed, what its present status is, what the major characteristics and limitations of the methods used to solve scientific questions are etc. In other words, it is essential that they themselves are literate in NoS in order to guide their students towards acquiring adequate scientific literacy.

This is where the task of teacher instructors at university level starts. Many **difficulties** are faced. First, the history of science and of chemistry in particular, is usually not part of the curriculum for chemistry bachelors or masters degrees. Teachers, therefore, frequently lack the knowledge of adequate examples,e.g.on science controversies, on which they can build their own reflection on how science has developed. Although chemistry bachelors are taught an historical introduction to philosophy, sometimes centred on the philosophy of science, in some countries, this is by no means general. In most cases, the philosophical background of future science teachers is quite limited. An obvious consequence of this situation is that future teachers, including 1st year teachers in higher education schools, usually hold somewhat limited and poorly developed conceptions of the epistemological dimensions of their discipline. This has been analysed in many studies (Van Driel & Verloop, 1999; Lin & Chen, 2002; Justi & Gilbert 2003; Bartholomew et al., 2004; Chen, 2006; Liang et al., 2009; Niaz, 2009; Buffler et al., 2009; Mugaloglu & Bayram, 2010; Karakas 2011; Markic & Eilks 2012; Bektas et al., 2013; Ozgelen et al., 2013; Vásquez-Alonso et al., 2013; Abd-El-Khalick 2013; Roth & Weinstock 2013; Briell et al., 2013; Mazzarone & Grove, 2013; Topcu, 2013; and references cited in these papers).

Furthermore, chemistry students and pre-service teachers are often reluctant to reflect about philosophical issues which they feel remote from real-life chemistry. It is therefore essential to convince them of the relevance of this. As will be discussed later (Case Study section), this can be achieved by having them work in interdisciplinary groups to foster discussions among peers, by identifying their preconceptions about NoS, by selecting topical examples oriented towards physics, chemistry and biology to infer or illustrate abstract concepts, and by showing them possible applications in their future roles as teachers.

Theoretical framework

Approaches for teaching Nature of Science and assessment methods

Research on developing NoS understanding among secondary school students and among teachers (at either pre-service or in-service stage) has evolved mainly along the following lines with obviously some overlap between related fields:

a) development of quantitative and qualitative tools to assess learners' epistemological views (Further Reading: Lederman et al., 1998; Deng et al., 2011) (Chen, 2006; Liang et al., 2009; Mugaloglu & Bayram, 2010; Karakas 2011; Markic & Eilks, 2012; Vásquez-Alonso et al., 2013; Briell et al., 2013);

b) analysis of the learners' NoS views and of the factors influencing them (Further Reading: Deng et al., 2011) (Van Driel & Verloop, 1999; Hogan, 2000; Osborne et al., 2003; Treagust et al., 2004; Liang et al., 2009; Buffler et al., 2009; Mugaloglu & Bayram, 2010; Karakas, 2011; Markic & Eilks, 2012; Bektas et al., 2013; Roth & Weinstock, 2013; Briell et al., 2013; Mazzarone & Grove, 2013; Topcu, 2013; Metallidou, 2013; Kremer & Mayer, 2013) ;

c) analysis of epistemological views transmitted by textbooks, either at secondary or higher education level (Further Reading: Niaz & Maza, 2011) (Bensaude-Vincent, 2007; Abd-El-Khalick et al., 2008);

d) curriculum definition, design and critical analysis of learning activities focussed on improving the learners' epistemological literacy (Further Reading: McComas et al., 1998; Abd-El-Khalick & Lederman, 2000a; Abd-El-Khalick & Lederman, 2000b; Vesterinen & Aksela, 2013) (Matthews, 1998; Turner & Sullenger, 1999; Justi & Gilbert, 2000; Lin & Chen, 2002; Gilbert, 2004; Bartholomew et al., 2004; Dass, 2005; Holbrook & Rannikmae, 2007; Taber, 2008; Prins et al., 2008; Niaz, 2009; Pluta et al., 2011; Reiners, 2012; Eastwood et al., 2012; Ozgelen et al., 2013; Abd--El-Khalick, 2013; Duschl & Grandy, 2013, Wan et al., 2013);

e) comparison between NoS views recommended by philosophers of science and those adopted by science practitioners (Van Der Valk et al., 2007; Schwarz and Ledermann, 2008; Wong & Hodson, 2009).

It is not possible here to review even briefly all this research. We propose to focus on selected aspects relevant for our purpose and therefore related to good practice in developing NoS understanding and competencies in pre-service secondary school teacher education.

The first question which arises when designing a NoS course is: What should be taught? We leave this essential question for the next subsection, which is devoted to the curricular aspects. We would just like, as a preview, to mention here that we share Matthews' opinion (Matthews, 1998), in its "Defense of Modest Goals When Teaching about the Nature of Science".We are convinced that transforming chemistry teachers into science philosophers is utopian. <u>If we wish to succeed in motivating future science teachers towards NoS we should rather focus on essential but reasonable ("modest") goals</u>.

As discussed by Abd-El-Khalick and Lederman (Further Reading: 2000a), the different approaches used to strengthen the NoS understanding for future secondary school teachers belong to two categories: *implicit* and *explicit* methods. Implicit approaches assume that by having learners (either secondary school students or pre-service or even in-service teachers) solve tasks requiring scientific approaches (e.g. inquiry-based approaches), they will *necessarily* acquire the adequate epistemological understanding, which appears therefore as a natural *affective* learning outcome. Explicit approaches require, as the word implies, that the epistemological concepts (tentative nature of scientific knowledge, evidence-based nature, role of models and theories etc.) be explicitly discussed in the learning situations. The latter can be of various types: theoretical lectures, inquiry, or analysis of historical cases. NoS understanding appears here as a *cognitive* learning outcome. The conclusion reached by Abd-El-Khalick and Lederman in their literature review clearly advocates the explicit approach: "… even though any attempt to foster better understandings of NoS among science teachers should be framed within the context of the content and activities of science, these attempts, nevertheless, should be explicit and reflective. It is essential that teachers be provided with conceptual frameworks that should help them to construct better understandings of certain aspects of NOS.” (Further Reading: Abd-El-Khalick & Lederman, 2000a, p. 691) Examples and discussion of explicit approaches are developed in several references (Further Reading: McComas, 1998; Vesterinen & Aksela, 2013) (Lin & Chen, 2002; Dass, 2005; Niaz, 2009; Reiners, 2012; Duschl & Grandy, 2013). Some of the methods proposed and discussed in these studies refer to the analysis of historical cases or controversies (Further Reading: Abd-El-Khalick & Ledermann, 2000b) (Lin & Chen, 2002; Dass, 2005; Niaz, 2009). History-based approaches seem also more efficient when the epistemological aspects are explicitly reflected upon. In the next section, we describe a practical explicit approach developed at the University of Liège for pre-service biology, chemistry and physics teachers.

The many studies cited above which have examined the NoS views of pre- or in-service teachers reach similar conclusions. The observed level of understanding is usually inadequate, which means, more precisely, too simplistic and not consistent. The epistemological views of assessed and/or interviewed teachers do not *fully* correspond to the present accepted view of philosophers of science (usually denoted in the literature as “informed view”), which will be tentatively summarized in the next subsection. Teachers’ beliefs are in fact quite diverse and mixed. While some overlap is observed between the actual and the informed conceptions, the most significant conclusion is that there is a lack of consistency about the views expressed by teachers, a situation which makes it difficult to assign them to recognized philosophical schools of thought e.g. positivist *versus* constructivist. A few of the cited studies focus specifically on the teachers’ understanding of the nature and function of models. For example, Van Driel and Verloop (1999) conclude that “… experienced teachers, though they share the general notion that a model is a simplified representation of reality, may have quite different cognitions about models and modelling in science.” (p. 1150) These authors add that “Some functions and characteristics of models were rarely mentioned by these teachers (e.g. using models to make predictions, or perceiving a model as a tool for obtaining information about a target which is inaccessible for direct observation).” Justi and Gilbert (2003) emphasize the lack of “coherent ontological and epistemological views [of teachers]” (p. 1382). They also note that the chemistry and physics teachers interviewed in their study showed a more comprehensive understanding of the notion of model than their biology colleagues. For example, most of the biology teachers but none of the physicists or chemists believed that a model cannot be modified. The authors suggest that the reason may lie in the more frequent contact with models in physics and chemistry education. Liang et al. (2009) investigated pre-service science teacher views in China, Turkey and the United States of America. Their study reveals common patterns (the tentative nature of science is better understood than the concepts of theories and laws) but also some culturally-anchored differences: e.g. theories have a more respected status in Chinese culture than in the U.S.A. where the hypothetical aspect of a theory is likely to be overemphasized.

Many quantitative and qualitative tools exist for assessing the NoS views of the different categories of learners and teachers. They are extensively used in most of the works cited and discussed above. They have been critically reviewed by Lederman et al. (Further Reading: 1998). The current tendency is to favour qualitative approaches based on interviews and open-ended questions which, despite a more complex and less objective data handling procedure, have the following advantages: (i) contrary to multiple choice questions, they avoid pre-orientating the answers of the assessed people; (ii) oral interviews may remove ambiguities and misunderstandings and allow the interviewees to be more explicit. Some studies combine both approaches.

Nature of Science curriculum for pre-service teachers

The first problem which arises when trying to define a curriculum for NoS teaching and learning at the pre-service teacher level is to find a consensus view of NoS. It must be emphasized that a consistent, consensus-based view of the Nature of Science, does not exist at the present time. Even worse, as noted by Turner and Sullenger (1999), "Educational theorists have turned their attention to the nature of science at a moment of minimal consensus, when science appears to have many natures rather than one. Equally curious, educators have done this in a dangerous period of mounting public controversy, as strongly entrenched defenders of science square off against postmodernists real and imagined." (p. 6) As mentioned in the introduction, the literature on epistemology and philosophy of science is extremely rich, which makes it difficult to have a unified view appropriate for teaching. Most textbooks available are, in addition, relatively theoretical and not adapted for an audience of future science teachers. A few recent textbooks in English which could be appropriate for the interested reader are mentioned in the Further Reading Section: Chalmers (2006), Losee (2001), Okasha (2002) and Gimbel (2011).

Nevertheless, despite the controversies among philosophers of science, there exists some kind of a consensus about common characteristics of all scientific approaches, which are agreed upon by basically all science education specialists. These common features are summarized in several papers and are given in Box 1, based on selected publications (Niaz, 2009; Abd-El-Khalick et al., 2008). We intend to restrict our considerations to key-concepts which are likely to be useful in real classroom situations.These are listed in Box 2. A possible methodology will be discussed in the section describing a case study.

Box 1. A minimal consensus about the Nature of Science

1) Science is tentative and subject to change and evolution.
2) Scientific knowledge relies on both empirical evidence (observation and experience) and rational inferences.
3) Science is theory-laden. Theory affects the definition of the research questions and also the experiments, that is, how they are designed and how the data are handled.
4) There is no unique, universal, algorithm-type scientific method but rather different approaches depending on the research field and the problem to be tackled.
5) Theories are the result of the creative, speculative imagination of scientists. Competition among theories drives scientific progress.
6) Theories and laws are different concepts which do not possess any hierarchical relationship. A law is not a confirmed theory.

7)	Accurate recording of the data, reproducibility tests and peer-review are essential guard rails.
8)	Social, political, economic and cultural conditions influence the way scientific ideas are developed.

Box 2. What should be taught to pre-service teachers?

1) Definitions: Nature of Science, epistemology, philosophy of science
2) Nature of knowledge
    a) Kant's constructivism as a synthesis of rationalism and empiricism
    b) Piaget's constructivism
    c) Socio-constructivism[2].
3) Scientific approaches: important philosophers of the 20th century
    a) Can the scientific method be defined? P. Feyerabend
    b) T.S. Kuhn: "The structure of scientific revolutions"
    c) K. R. Popper: "The logic of scientific discovery"
4) Scientific approaches: the most important "ingredients", i.e., the most important concepts used daily by a scientist
    a) Questioning in science
    b) Central role of observation and experimentation – Reliability of experimental data
    c) Hypotheses
    d) Models
    e) Theories
    f) Confrontation between models/theories and reality (respect of evidence)
    g) What do we mean when using the words "explanation" and "understanding"?
5) Relationships between the scientific development at a given period of history and the social, political, economic, and cultural situation at that time.

A few comments are appropriate here. Considering the importance of socio-constructivism in the present theories of education[2], it seems important to show where its roots lie. This also gives the opportunity to discuss important trends in the evolution of western ideas about science. References to the history of science can be made at different points in such a presentation. As an example, the way Galileo Galilei combined the design of relevant experiments (astronomical observations using telescopes, or experiments on kinematics) with mathematical modelling based on Euclidian geometry illustrates perfectly the two aspects of modern science which the word "constructivism" implies (even though this word did not exist at Galilei's time): rationalism, that is, mentally constructing scientific

[2] see also the chapter http://files.gandi.ws/gandi22757/file/ec2e2n_book-201511-Guidebook_GoodPractice_4PSTCT-Chap01.pdf

objects (models and theories), and empiricism, that is, confronting these models or theories with the experimental evidence (for more detail, see the case study and Figure 1).

An adequate, informed understanding of the major concepts used by scientists is an essential part of scientific literacy. We share Matthews' view that "It is unrealistic to expect students or prospective teachers to become competent historians, sociologists, or philosophers of science. We should have limited aims in introducing epistemological and nature of science questions in the classroom.[…] Philosophy is not far below the surface in any science classroom. At a more basic level any text or scientific discussion will contain terms such as *law, theory, model, explanation, cause, truth, knowledge, hypothesis, confirmation, observation, evidence, idealization, time, space, fields,* and *species*. [...] A professional teacher should be able to elaborate a little on these matters." (Matthews, 1998, p. 168)

Finally, a discussion on the relationships between the scientific development and the socio-political situation can open interesting questions on the absolute (or not) nature of scientific knowledge and on the relationships between science and society.

Case Study: a practice-based approach to introduce key aspects of the Nature of Science to pre-service biology, chemistry and physics teachers

This practical approach aims to take into account the various goals and constraints described in the previous sections.The present proposal is inspired by the experience of teaching the Nature of Science to a mixed group of future biology, chemistry and physics secondary school teachers (between 30 and 50 students each academic year) at the University of Liège (Belgium). The course has been assessed (and has evolved accordingly) over the last nine years. A particularly strong constraint is the limited time available (8 hours), which represents about 10 % of the total time devoted to the course in science education for pre-service secondary school teachers in Liège[3]. In the following, we present a chronological description of the four successive seminars (about 2 hours each) devoted to this topic. Box 3 gives an overview.

Box 3. Organization of the NoS seminars at the University of Liège (Belgium)

1st seminar:

a) Presentation of the general framework of the seminars

b) Teamwork based on questions presented in Table 4: each group works on one question

2nd seminar: Status of science, scientific truth, philosophical basis of socio-constructivism

[3] The pre-service chemistry teachers, e.g., follow 75 lecture hours devoted to chemical education, also called "didactics for chemistry". Equivalent courses are organized for biologists and physicists. In addition, they have school placements (40 hours) and courses on general didactics, psychology, sociology, ethics, class management etc.

3rd seminar:

a) Some key-concepts of science (I) with a focus on hypothesis, model, theory

b) Kuhn's theory of scientific revolutions

4th seminar:

a) Some key-concepts of science (II) with a focus on discovery, explanation and understanding

b) Science is socially, politically, economically, and culturally embedded.

In addition to what is done in practice at the University of Liège, supplementary material has been added for the purpose of the present paper. It is clear that the coverage is probably too broad for 8 to 10 hours teaching but as the seminars are designed to be largely interactive, the developed content can be varied – within limits – depending on the attendees' preconceptions and reactions.

1st Seminar

The first part of the seminar is a general presentation which aims at defining the objectives of the seminars: why is the topic important, what are the legal requirements for secondary school teaching, how will the seminars be organised.

Four questions (Box 4) are then submitted to the pre-service teachers, subsequently referred to as participants in the following discussion, in order to assess their preconceptions on the topic "Nature of Science". These questions are first presented in detail by the lecturer using concrete examples. The participants are then asked to work in interdisciplinary teams of 4 to 6 people, each group dealing with one question during approximately 80 minutes. If there are too many participants, the same question can be dealt with by several teams. At the end of the seminar, each team hands in a report of about one to two A4 pages. These reports will be used as reference points in the following three seminars. The advantage of this procedure is that the participants will already have thought about the questions before they are discussed in the seminars, and interactions between the lecturer and the participants are therefore likely to be more spontaneous: whenever theoretical concepts are discussed, reference can be made to the participant reports.

Box 4. Questions for interdisciplinary team work

For each question, the future teachers are requested to illustrate their ideas with practical examples.

1) What are the specific contributions of science courses to the education of secondary school students? Why are they essential? How would you defend them in front of a minister for education? What does the expression “scientific truth” mean, to you and to the general public?
2) How would you characterize scientific approaches or methods? What are, in this framework, the essential points you want to make your school students aware of and confident with? How would you define or describe a model and a theory?
3) What do the verbs “discover”, “explain”, and “understand” mean in a scientific context?
4) Argue in favour or against the fact that science is politically, economically, socially and culturally embedded.

2nd Seminar

The second seminar is mostly devoted to the first question in Box 4, which leads to a discussion of the **status of science** and its relationship to the problematic concept of **truth**. How the seminar evolves depends on the reports of the participants, which vary from year to year, but, usually, they reach the conclusion that the generic aim of science courses is twofold:

1) teaching a scientific approach to consider the world;
2) providing the secondary school students with tools that make them better able to understand the world and to be responsible citizens.

The pre-service teachers usually agree that science is part of the culture of a civilization and that science has the ambition to say “something true” about the world, or at least about phenomena. This leads naturally on to a discussion of whether we are tending to an absolute knowledge or whether our knowledge is a construct of the human mind. This has obvious consequences for both the status of science and the way in which it is taught, as illustrated by socio-constructivist approaches.

Different questions may arise at this point. Whether they are discussed briefly or extensively is guided by the reactions of the participants. For example, the question of absolute truth or variability of theories with time can be discussed in more detail, arguing that we can distinguish between theories that are completely wrong and have been discarded, and theories that need to be modified over time but contain a central nucleus of truth that becomes more and more corroborated. The phlogiston theory is an example of the former, Dalton’s atomic theory of the latter. Alternatively, this question can be dealt with in the third seminar, after the presentation of Kuhn’s view of the development of science.

The previous discussion is the starting point for a more theoretical presentation by the lecturer, which aims at organizing the somewhat diffuse ideas of the pre-service teachers into a more logically consistent and rigorous framework. The major goal is to show how a constructivist approach reconciles the empirical and rationalist approaches of acquiring knowledge, leading to the current conception that (see Box 1, item 2) *scientific knowledge relies on both empirical evidence (observation and experience) and rational inferences*.

Figure 1 below summarizes the major concepts discussed at some length in this second seminar.

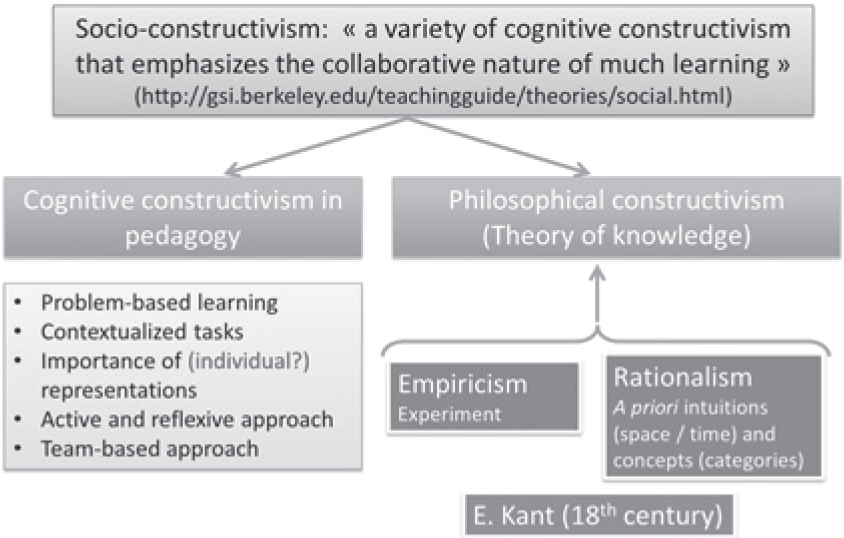

Figure 1.Empiricism, rationalism and constructivism: a synoptic view

This may be the place to discuss the reliability of experimental data. Who controls this? The answer might be that a definitive control is actually impossible, that unreliable data have been published and will likely continue being published, but the strength of the scientific methods is that false data are recognized and rejected in the long run, though they can be a source of much trouble and confusion in the short term. Alternatively, this essential aspect can be dealt with in the third seminar.

3rd seminar

The third seminar deals with the 2nd question in Box 4, which is concerned with the **scientific methods** themselves. These are usually presented in secondary school or freshman textbooks as “the scientific method” using an algorithmic approach with several feedback loops involving elements like “observations”, “hypotheses”, “laws”, “models” and “theories”. This also corresponds very often to the spontaneous representations of the future teachers. The first step is to question this somewhat simplistic approach, by making a short reference to the work of P. Feyerabend (2010; the original edition was published in 1975).

Quite often, the participants emphasize the following aspects:

1) The scientific method is oriented toward solving defined problems. This raises the essential point of questioning in science, which is also linked to its theory-driven nature.
2) The approach must be structured: as already mentioned, the future teachers favour an algorithm-like scientific approach.
3) Experimental data must be reproducible.
4) Nothing has to be accepted *a priori*.
5) Scientists have to be critical and open to criticism or review from peers.
6) Scientific theories have to be interpreted in the space and time contexts of their development.

Based on these preconceptions, which contain many interesting elements, it is suggested that one might continue with two further steps. First, some of the above-mentioned characteristics of the scientific approaches can be discussed in more detail. We emphasize two of these in the following paragraphs. We leave for the last seminar the discussion on the links between science and its societal context. In a second step, a more conceptual discussion based on T.S. Kuhn’s views is presented (Further Reading: Kuhn, 1996; originally published in 1962).

As stated above (2^{nd} seminar), this might be the appropriate place to analyse how – and how efficiently – the reliability of experimental data is controlled.This is of course linked to our understanding of the nature of uncertainties in the measurements. Buffler et al. (2009) propose that there is a relationship between the NoS views of students and the way they consider the reliability of scientific measurements.

A central point is the **questioning** nature of science. This is a key first step in developing scientific theories, as scientists question the world around them. This is a step that is too often neglected in school and university level science, as teachers tend to dictate the kinds of questions and investigations that the students look into. This is understandable from a practical point of view but it can mean that school students are denied the opportunity to follow their own questions and interests, although this is the approach that tends to be employed in primary school science. The importance of questioning as part of the nature of science and the role it plays in scientific practice must thus be emphasized and reasonable approaches to combine the curiosity and the freedom of thought of school students with the requirements of the school curricula need to be discussed. Questioning in science is directly linked with the theory-laden nature of science. The scientific situation at a given time and in a given field is always analysed based on the existing conceptual explanation frames, that is, on the existing *theories*, which are part of what Kuhn calls a *paradigm*. Questioning has therefore two facets: a *cognitive* one linked with an adequate mastering of the relevant paradigm(s) and a *psychological* one, which is much more difficult to address. Questioning in the classroom cannot be compared directly with questioning in the laboratory because the scientific culture of school students and experienced researchers are incommensurable. It is therefore recommended, when the teaching goal is to promote questioning skills, to carefully select the inquiry context. In a research report on the “Selection of Authentic Modelling Practices as Contexts for Chemistry Education”, Prins et al. (2008) note, based also on previous work by different authors, that “there is no fundamental difference between the thinking of children and adults (experts), except when accounting for domain specific knowledge" (p. 1872). They further suggest criteria for choosing contexts for inquiry-based modelling practices:

- school students' interest and motivation;
- possibility for the students to develop autonomy;
- required modelling for the specific context in line with common sense and pre-existing modelling capabilities;
- complex task but with some familiarity with the issues the school students are used to;
- relevant laboratory work compatible with the classroom environment.

Even though this report focusses on the development of modelling skills, we believe that at least some of the proposed criteria are also relevant for questioning skills.

These different preconceptions call for a deeper analysis, which can be performed, e.g., in the framework of T.S. Kuhn thesis on the structure of scientific revolutions (Further Reading: Kuhn, 1996). Important concepts like "*paradigms*", "*normal science*", "*crisis*", "*scientific revolutions*" are then discussed. This theoretical presentation needs to be illustrated by different examples. One of them, particularly appealing for future physics teachers if they are part of the audience, is the foundation of quantum mechanics, when science was able to take into account new facts and data without renouncing long-established theories, but rather framing them in their proper field of validity, and developing completely new concepts. This leads to a pedagogical question: should quantum-mechanical principles be taught by analogies with classical systems, or should they simply be presented as axioms? For chemists, the historical example of the analysis and synthesis of water by Lavoisier is a very good illustration of the role of a paradigm (quantitative conservation of matter). The quality of the experiments of Lavoisier (role of the evolution of the experimental tools, high quality balances) can also be emphasized here, in relation to the previous discussion on the reliability of experimental data. This theoretical presentation and the associated examples, illustrate, in a complementary perspective, the problems of 'questioning' (in "normal science" or in a "crisis period").

The last part of the seminar is then devoted to deepening of important concepts, mainly concerning the different kinds of models and theories[4]. Pre-service teachers' understanding on these two central concepts is, in agreement with the research literature (see Theoretical framework section), generally very simplistic. They are usually unable to deduce from actual models the general criteria which a good model has to fulfil. Emphasis is therefore put on discussing several examples and on identifying the differences and similarities between the use of models in physics, chemistry and biology. Examples in biology include the eukaryote cell, the lock-and-key model in enzymology, or animal models in pharmacology. In chemistry, models like the electronic shell model for atoms, the oxidation numbers, the ideal gas, the transition state model, the Brønsted-Lowry model (also called theory!) are discussed, with a special emphasis on the ideal gas, which is also relevant for pre-service physics teachers. In physics, the harmonic oscillator model is discussed in detail. This model also has important applications for chemists in molecular spectroscopy. It must be emphasized here that an important difference between chemistry and other sciences is that significant discussions in chemistry necessarily involve the use of sub-microscopic views.

[4] see also the chapter http://files.gandi.ws/gandi22757/file/ec2e2n_book-201511-Guidebook_GoodPractice_4PSTCT-Chap13.pdf

This theme is developed in the book devoted to teaching chemistry in higher education that was published in 2009 by ECTN through the Royal Society of Chemistry (Floriano et al., 2009).

The aim of this discussion is to identify, through an analysis of the different mentioned examples, a series of common properties which define a model and the following kind of definition should emerge: *A scientific model is a simplified representation of a real system or mechanism (called "the target"), which allows organizing and generalizing empirical data, which has an explanatory power when it is associated with a relevant theory, which allows making predictions that can be confronted with the experimental evidence, and which can then possibly be refined.* This definition can, in a further step, be compared with different definitions given in the literature. We chose to confront our definition with the common characteristics of models given by Van Driel and Verloop (1999) but other papers could also form the basis for such a comparison (Van der Valk et al., 2007, e.g.). We should also mention at this point a paper by Pluta et al. (2011) which reports on an experiment with secondary school students who were given the task of defining epistemic criteria for adequate models based on specific examples of models. When considered globally at the class level, the results were very encouraging, because at least three key criteria were identified in more than 80% of classes: accuracy, explanatory scope and parsimony[5].

The next step consists in discussing the concept of theory and differentiating it from that for model. The main conclusion to be reached is that *a theory establishes, based on assumptions often called postulates, internally consistent relationships between effects and causes* which make it possible to derive from them scientific laws which are quantitative formulae relating measurable physical quantities. Theories account for a large number of various empirical data. Theories are predictive and are therefore testable and fruitful in allowing the researchers to propose new or alternate investigations. As a consequence, they are also tentative and subject to improvements or possible rejection based on empirical evidence. These different aspects are summarized in Figure 2.

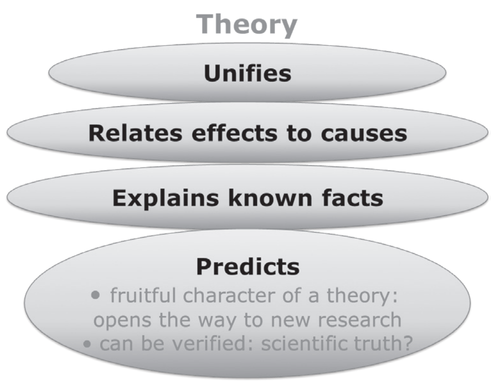

Figure 2. Main features of a scientific theory

As a conclusion to this third seminar, the distinction between scientific and non-scientific approaches and proposals can be dealt with. The ideas of K. R. Popper on the "Logic of

5 In the work of Pluta et al. (2011) "parsimony" means, following T.S. Kuhn, an appropriate choice of the simplification level of the model.

Scientific Discovery", originally published in German in 1934, can be mentioned in this context (Popper, 2002). If insufficient time is available, this point can be discussed in the last seminar.

4th Seminar

The final seminar is concerned with the last two questions submitted to the pre-service teacher teams (see Table 4), that is, scientific explanations and the relationships between science and society.

The contributions of the students are analysed in such a way that the nomo-logico-deductive character of the **scientific explanations** can be emphasized. The scientific explanation is presented as the *translation of a series of empirical data (example: haemophilia affects the sons but is transmitted by the mothers) in a vocabulary composed of abstract terms (genes, chromosomes etc.), whose definitions are known from the science practitioners (cf. Kuhn's paradigms) and whose interrelations are explicitly developed in an accepted, but always provisory, theory (cause-effect relationships, cf. Kant's* a priori *concepts)*. Such a theory is also part of Kuhn's paradigm. The concepts defined and discussed in the previous seminars can thus be fruitfully re-applied here. It is also possible to deal at this point with the distinction between scientific and non-scientific approaches and proposals.

Practical didactical implications are deduced. In assessment tasks in a competency-oriented framework, secondary school students are often asked to provide a scientific explanation for an original (at least for them) series of data, based on their previously acquired knowledge. The definition proposed above helps the teachers to identify the important steps in the explanation, providing them with specific checkpoints for grading (*Is the right vocabulary used? Did the school students identify the appropriate cause-effect relationships*? Etc.)

As a final but essential point, the **relationships between science and society** are dealt with. Many questions could be addressed in this quite broad field but we focus on one aspect: *is the way people do science (which science they do, how they do it) influenced by the general political, social, economic, and cultural conditions which determine the society at a given place and at a given time?* The so-called "sociology of scientific knowledge" began to develop in the late seventies and eighties with the work of Bloor (1976) and Collins (1983). An historical perspective of the development of science studies during the last 30 years is given by Pestre (Further Reading: 2004). When asked about examples of science-society relationships, the teachers usually emphasize the conflicts between science and religion and focus on contemporary examples or on famous historical events (Galilei). Geography and economy are also identified as influential.

Spontaneous comments by the students on these issues can be used to introduce ideas on the ethics of science. Historical examples (Galilei) can be developed but also more contemporary issues, such as global warming, animal testing, genetically modified organisms etc.

A different, less obvious but complementary perspective on the complex interrelations between science and society results from a detailed analysis of key-periods of history. The following three periods have been selected for the course at Liege, but these are only examples.

1) The birth of philosophy in Ionia in the 6th century BC: relationships between the organization of the city and the understanding of nature (”physis”);
2) The first signs of a new view of the world in the 14th century AD: relationships between the nature of knowledge, social organization and art (symbolism, representation of nature, perspective).
3) Research on the properties of light in the 17th century: science and painting.

A quotation, concerning the birth of philosophy in the 6th century BC, by J.-P.Vernant (2007) illustrates our purpose: “To build the new cosmologies, they [the Greeks] have used the concepts that moral and political thought had developed, they projected on the natural world this conception of order and law which, by triumphing in the city, had transformed the human world into a cosmos.”[6] The basic idea which we intend to transmit here is that our way of doing science and the basic concepts that we develop for this, e.g. laws, have their roots in very ancient history and are embedded in the cultural and political environments that prevailed at that time. The success of scientific enterprises over the centuries allows us to unravel the link to specific historical conditions and to free the scientific approaches from their ancient origins. However, in reality this represents a profound example of how science is invariably embedded in a more general context.

Assessment

It might be necessary, depending on the system adopted in each university, to assess the pre-service teachers on the topic developed in this chapter. EChemTest® questions are certainly useful to check the understanding of the students about key-concepts, like those discussed above. It is important, however, that questions be as contextualized as possible, and we refer back to our earlier discussion regarding quantitative and qualitative tools for assessing NoS conceptions (Theoretical framework section).

It is also important to make teachers aware of the need to deepen their understanding of this topic. This can be achieved by reading in the specialized literature chemistry (or biology, or physics) papers which are focused on very practical, education-oriented topics. A few examples are given by the recent work of Taber (2010), Graulich et al. (2010), Bensaude-Vincent (2007), and Buskirk & Baradaran (2009). Such papers can form the basis of an oral examination or of an assessed seminar, where the pre-service teachers could be invited to give a review presentation based on these papers. The oral examination alternative has been used at the University of Liège.

[6] Original text in French : *« Pour construire les cosmologies nouvelles, ils ont utilisé les notions que la pensée morale et politique avait élaborées, ils ont projeté sur le monde de la nature cette conception de l'ordre et de la loi qui, triomphant dans la cité, avait fait du monde humain un* cosmos.*»*
J.-P. Vernant, *Les origines de la pensée grecque*, Quadriges, Presses Universitaires de France, Paris (2007), p.106 The English translation has been done by the present authors.

Using 'History of Science' (especially chemistry) to teach NoS

Secondary school students can become aware of the nature of science by practicing it[7] but also by learning from history how science develops.

As already mentioned in the theoretical overview and advocated by many authors (Further reading: Abd-El-Khalick & Lederman, 2000b) (Justi & Gilbert, 2000; Lin & Chen, 2002; Dass, 2005; Niaz, 2009; and references cited therein), having students and pre-service teachers investigate selected periods of the history of science can lead to positive effects on the learners' understanding of NoS, provided reflection on the relevant epistemological aspects is explicitly promoted.

Teaching systematically the history of science *per se* is of course not the aim of a secondary school science class. It is, however, important that future science and chemistry teachers have a reasonable knowledge of the historical development of their scientific field. This gives them the opportunity to look at the nature of science through an historical lens which magnifies how science is evolving and developing in reality and not only in the minds of science philosophers. Alluding to specific historical events and steps in a science classroom can make the course lively and at the same time reveal some important aspects of scientific inquiry methods.

There are currently few books on the history of chemistry which are suitable as texts for future chemistry teachers. It is, in fact, important to recommend books which deal not only with historical aspects but also with recent developments. The work of T. H. Levere "*Transforming Matter*" (Further Reading: Levere, 2001) performs well in presenting a good-balanced story starting with alchemy and ending with new frontiers. In addition, its "Further Reading" section is well-developed. Another, somewhat more difficult textbook which focuses more on the way the identity of chemistry progressively evolved is "*A History of Chemistry"* by B. Bensaude-Vincent and I. Stengers (Further Reading: 1996).

History of Science textbooks are not generally well illustrated and therefore tend to appear quite dry. This, however, can provide a good opportunity to organize seminars, where the future teachers are required to illustrate selected chapters from a chosen book. The book defines the content to be covered but the teachers are strongly encouraged to try to make it as interesting as possible. The aim of these seminars can be twofold:

1) to make pre-service teachers better informed about key historical issues in chemistry, for example how controversies were solved, and their relationships to NoS;
2) to give them, in addition, the opportunity to reflect about concrete ways to implement these historical aspects into secondary school teaching to promote the understanding of NoS issues.

If time is limited, the focus may be restricted to the first of these two instruction goals.

To make the link between questioning and the nature of science, it is recommended that the participants put forward considered responses to the following questions when analysing a particular stage in the history of chemistry. This list is certainly not exhaustive.

1) What was the starting question, what was its origin, its roots?
2) What facts were available?

[7] see also the chapter http://files.gandi.ws/gandi22757/file/ec2e2n_book-201511-Guidebook_GoodPractice_4PSTCT-Chap05.pdf

3) Which hypotheses have been formulated?
4) How did one come to these hypotheses, in what context? (cf. the influence of Malthus' ideas on Darwin)
5) How did people react to the possible refutation of this (these) hypothesis(-es)?
6) How have the methods of investigation evolved (cf. atomic structure, molecular biology, e.g.)?
7) Which consequences of this evolution can be identified?
8) Why did one stop to consider (sometimes only temporarily) a given idea, a given concept?
9) Was that for scientific reasons (e.g. corpuscle nature of light)?
10) Or for ideological reasons (e.g. the atom, the vacuum)?

Conclusion

Promoting informed conceptions on the Nature of Science, a key aspect of scientific literacy, is a central goal in secondary school education. An obvious prerequisite is that secondary school teachers themselves hold an adequate understanding on the major characteristics of NoS and that they are able to elaborate on key-concepts like models and theories. Most research directed towards assessing teacher views on NoS pinpoint simplistic and non consistent conceptions (see Theoretical framework). There is therefore much to be done to improve pre-service teacher education on NoS, taking into account several constraints:

- lack of philosophical background;
- limited background on the history of science;
- lack of interest of chemists for philosophical issues;
- usually a limited availability of time within the pre-service teacher education curriculum.

Analysis of the literature also reveals that explicit approaches to NoS have the highest efficiency.

Seminars organized in the framework of the pre-service education for biology, chemistry and physics teachers at the University of Liège (Belgium), details of which are illustrated by the concept map displayed in Figure 3, attempt to solve at least partly these problems

- by first identifying the preconceptions of the learners through team work,
- by introducing and discussing explicitly key theoretical concepts based on the identified preconceptions
- by promoting an inductive approach, which starts from practical examples (specific models, e.g. from biology, chemistry and physics), to infer key abstract concepts,
- by highlighting the pedagogical applications,
- by making frequent references to the recent research literature.

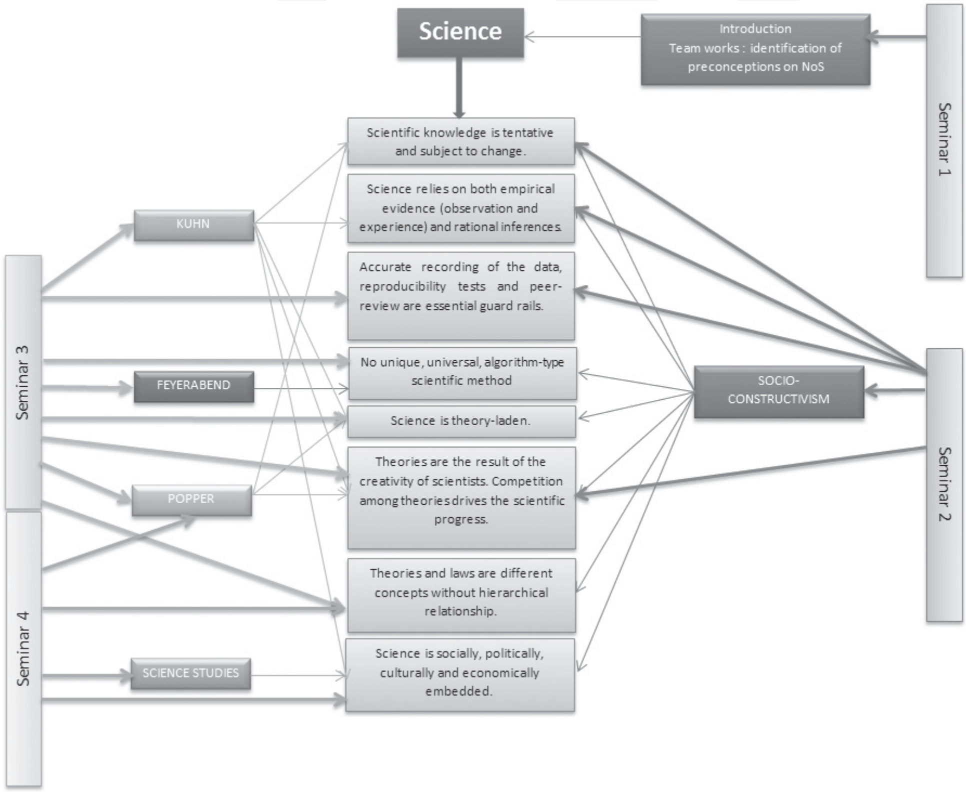

Figure 3. Concept map for the NoS seminars at the University of Liège (Belgium)

Our discussion, up to now, has been mainly concerned with pre-service teacher education. This approach could, however, be easily adapted to in-service education. We would recommend organizing four half-day seminars with the same partitioning as described previously. Compared to our four two-hour seminars, a four-afternoon option would allow the teachers to spend more time on the collaborative work and to elaborate more deeply on their preconceptions. This would also leave enough time to discuss in more detail pedagogical issues linked to NoS. Ideally, a fifth afternoon could be devoted to further collaborative work, where teachers would design learning activities which aim at promoting the epistemological understanding of their secondary school students.

The present authors believe that less than four two-hour seminars is not an appropriate option. If time constraints are really unavoidable, we would suggest skipping the final topic, that is, the socially embedded character of science (Vision II of scientific literacy as defined by Roberts (2007)).

Probably, the most difficult aspect of teaching chemistry learners about NoS is to convince them that it is important, not merely esoteric and without any relevance. In other words, it can be difficult to keep them on board. Our experience has convinced us that fostering an on-going dialogue with the learners, based on their preconceptions, and adopting an inductive approach (from the secondary school teaching examples to the abstract concepts) certainly help to cross the activation barrier. Even though the height of the pedagogical activation barrier is hard to reduce because the NoS philosophical concepts are intrinsically difficult to grasp (but remember that clarity of the instructor's discourse can doubtless help), motivation to learn can nonetheless be substantially improved by adequate scaffolding and by emphasizing relevance in the classroom.

Further reading

Abd-El-Khalick, F., & Lederman, N. G. (2000a). Improving science teachers' conceptions of nature of science: a critical review of the literature. *International Journal of Science Education, 22*(7), 665-701

Abd-El-Khalick, F., & Lederman, N. G. (2000b). The Influence of History of Science Courses on Students' Views of Nature of Science. *Journal of Research in Science Teaching, 37*(10), 1057-1095

Bensaude-Vincent, B., & Stengers, I. (1996). *A History of Chemistry*. Harvard University Press, Harvard

Chalmers, A.F. (2006). *What is this thing called Science?* (3rd edition). Open University Press, McGraw-Hill, Maidenhead

Deng, F., Chen, D.-T., Tsai, C.-C., & Chai, C. S. (2011). Students' Views of the Nature of Science: A Critical Review of Research. *Science Education, 95*(6), 961-999

Gimbel, S. (Ed.) (2011). *Exploring the Scientific Method. Cases and Questions.*The University of Chicago Press, Chicago

Kuhn, T.S. (1996). *The Structure of Scientific Revolutions* (3rd edition). The University of Chicago Press, Chicago

Lederman, N. G., Wade, P. D., & Bell, R. L. (1998). Assessing the Nature of Science: What is the Nature of our Assessments? *Science and Education, 7*, 595-615

Levere, T.H. (2001). *Transforming Matter. A History of Chemistry from Alchemy to the Buckyball*. The Johns Hopkins University Press, Baltimore

Losee, J. (2001).*A Historical Introduction to the Philosophy of Science* (4th Ed.). Oxford University Press, Oxford

McComas, W. F., Almazroa, H., & Clough, M. P. (1998). The Nature of Science in Science Education: An Introduction. *Science & Education, 7*, 511-532

Niaz, M., & Maza, A. (2011). Nature of Science in General Chemistry Textbooks.*Springer Briefs in Education, 2*, 1-43

Okasha, S. (2002). *Philosophy of Science. A Very Short Introduction*. Oxford University Press, Oxford

Pestre, D. (2004). Thirty years of science studies: knowledge, society and the political. *History and Technology*, *20*(4), 351-369

Vesterinen, V.-M., & Aksela, M. (2013). Design of Chemistry Teacher Education Course on Nature of Science. *Science & Education, 22*(9), 2193-2225

References

Abd-El-Khalick, F., Waters, M., & Le, A.-P. (2008). Representations of Nature of Science in High School Chemistry Textbooks over the Past Four Decades. *Journal of Research in Science Teaching, 45*(7), 835-855

Abd-El-Khalick, F. (2013). Teaching *With* and *About* Nature of Science, and Science Teacher Knowledge Domains. *Science & Education, 22*(9), 2087-2107

American Association for the Advancement of Science (1989). *Project 2061: Science for all Americans*. Washington D. C. Retrieved from http://www.project2061.org/publications/sfaa/online/sfaatoc.htm

American Association for the Advancement of Science (1993). *Benchmarks for Science Literacy.* Oxford University Press, New York. Retrieved from http://www.project2061.org/publications/bsl/online/index.php

Bartholomew, H., Osborne, J., & Ratcliffe, M. (2004). Teaching Students "Ideas-About-Science": Five Dimensions of Effective Practice. *Science Education 88*(5), 655-682

Bektas, O., Ekiz, B., Tuysuz, M., Kutucu, E. S., Tarkin, A., & Uzuntiryaki-Kondakci, E. (2013). Pre-service chemistry teachers' pedagogical content knowledge of the nature of science in the particle nature of matter. *Chemistry Education Research and Practice, 14*, 201-213

Bensaude-Vincent, B. (2007). College Chemistry: how a textbook can reveal the values embedded in chemistry. *Endeavour, 31*(4), 140-144

Bloor, D. (1976). *Knowledge and Social Imagery*. Routledge, London

Briell, J. E., Elen, J., & Clarebout, G. (2013). Seeking Convergent Evidence of Epistemological Beliefs: A Novel Survey. *Electronic Journal of Research in Educational Psychology, 11*(2), 473-500

Buffler, A., Lubben, F., & Bashirah, I. (2009). The Relationship between Students' Views of the Nature of Science and their Views of the Nature of Scientific Measurement. *International Journal of Science Education, 31*(9), 1137-1156

Buskirk, A., & Baradaran, H. (2009). Can Reaction Mechanisms Be Proven? *Journal of Chemical Education, 86*(5), 551-558

Chen, S. (2006). Development of an Instrument to Assess Views on Nature of Science and Attitudes Toward Teaching Science. *Science Education 90*(5), 803-819

Collins, H.M. (1983). An Empirical Relativist Programme in the Sociology of Scientific Knowledge. Knorr-Cetina, K.D., & Mulkay, M. (Eds.) *Science Observed*, Sage, London

Dass, P. M. (2005). Understanding the Nature of Scientific Enterprise (NOSE) through a Discourse with Its History: The Influence of an Undergraduate 'History of Science' Course. *International Journal of Science and Mathematics Education, 3*(1), 87-115

Dillon J. (2009). On Scientific Literacy and Curriculum Reform. *International Journal of Environmental & Science Education, 4*(3), 201 – 213.

Duschl, R. A., & Grandy, R. (2013). Two views about Explicitly Teaching Nature of Science. *Science & Education, 22*(9), 2109-2139

Eastwood, J. L., Sadler, T. D., Zeidler, D. L., Lewis, A., Amiri, L., & Applebaum, S. (2012). Contextualizing Nature of Science Instruction in Socioscientific Issues. *International Journal of Science Education, 34*(15), 2289-2315

Feyerabend, P. (2010). *Against Method* (4th edition). Verso, London

Floriano, M. A., Reiners, C. S., Markic, S., & Avitabile, G. (2009). The Uniqueness of teaching and learning chemistry. Eilks, I., & Byers, B. (Eds), *Innovative Methods of Teaching and Learning Chemistry in Higher Education*, 23-42. RSC Publishing, Cambridge

Funtowicz, S. O., & Ravetz, J. R. (1994). Uncertainty, Complexity and Post-Normal Science. *Environmental Toxicology and Chemistry*, *13*(12), 1881-1885

Gilbert, J. K. (2004). Models and Modelling: Routes to more Authentic Science Education. *International Journal of Science and Mathematics Education, 2*(2), 115-130

Graulich, N., Hopf, H., & Schreiner P. R. (2010). Heuristic thinking makes a chemist smart. *Chemical Society Reviews, 39*(5), 1503-1512

Hogan, K. (2000). Exploring a Process View of Students' Knowledge about the Nature of Science. *Science Education, 84*(1), 51-70

Holbrook, J., & Rannikmae, M. (2007). The Nature of Science Education for Enhancing Scientific Literacy. *International Journal of Science Education, 29*(11), 1347-1362

Justi, R., & Gilbert, J. (2000). History and philosophy of science through models: some challenges in the case of 'the atom'. *International Journal of Science Education, 22*(9), 993-1009

Justi, R., & Gilbert, J. (2003). Teachers' views on the nature of models. *International Journal of Science Education, 25*(11), 1369-1386

Karakas, M. (2011). Science Instructors' Views of Science and Nature of Science. *The Qualitative Report, 16*(4), 1124-1159

Kremer, K., & Mayer, J. (2013). Entwicklung und Stabilität von Vorstellungen über die Natur der Naturwissenschaften. *Zeitschrift für Didaktik der Naturwissenschaften, 19*, 77-101

Liang, L. L., Chen, S., Chen, X., Kaya, O. N., Adams, A. D., Macklin, M., & Ebenezer, J. (2009). Preservice Teachers' Views about Nature of Scientific Knowledge Development: An International Collaborative Study. *International Journal of Science and Mathematics Education, 7*(5), 987-1012

Lin, H.-S., & Chen, C.-C. (2002). Promoting Preservice Chemistry Teachers' Understanding about the Nature of Science through History. *Journal of Research in Science Teaching, 39*(9), 773-792

Markic, S., & Eilks, I. (2012). A Comparison of Student Teachers' Beliefs from Four Different Science Teaching Domains Using a Mixed Methods Design. *International Journal of Science Education, 34*(4), 589-608

Matthews, M.R. (1994). *Science Teaching. The role of History and Philosophy of Science.* Routledge, London

Matthews, M. R. (1998). In Defense of Modest Goals When Teaching about the Nature of Science. *Journal of Research in Science Teaching, 35*(2), 161-174

Mazzarone, K. M., & Grove, N. P. (2013). Understanding Epistemological Development in First- and Second-Year Chemistry Students. *Journal of Chemical Education, 90*(8), 968-975

Metallidou, P. (2013) Epistemological beliefs as predictors of self-regulated learning strategies in middle school students. *School Psychology International 34*(3), 283-298

Mugaloglu, E. Z., & Bayram, H. (2010). A Structural Model of Prospective Science Teachers' Nature of Science Views. *Scandinavian Journal of Educational Research, 54*(6), 597-614

National Research Council (1996). *National Science Education Standards*. National Academy Press, Washington D.C.

Niaz, M. (2009). Progressive transitions in chemistry teachers' understanding of nature of science based on historical controversies. *Science & Education, 18*(1), 43-65

Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: a review of the literature and its implications. *International Journal of Science Education, 25*(9), 1049-1079

Ozgelen, S., Yilmaz-Tuzun, O., & Hanuscin, D. L. (2013). Exploring the Development of Preservice Science Teachers' Views on the Nature of Science in Inquiry-Based Laboratory Instruction. *Research in Science Education, 43*(4), 1551-1570

Pluta, W. J., Chinn, C. A., & Golan Duncan, R. (2011). Learners' Epistemic Criteria for Good Scientific Models. *Journal of Research in Science Teaching, 48*(5), 486-511

Popper, K. R. (2002). *The Logic of Scientific Discovery* (2nd edition). Routledge, London

Prins, G. T., Bulte, A. M. W., van Driel, J. H., & Pilot, A. (2008). Selection of Authentic Modelling Practices as Contexts for Chemistry Education. *International Journal of Science Education, 30*(14), 1867-1890

Reiners, C. S. (2012). Learning to Teach Nature of Science.The impact of an Explicit Approach. *Proceedings ICCE-ECRICE. La Chimica nella Scuola, XXXIV* (3), 298-301

Roberts, D.A. (2007). Scientific Literacy/Science Literacy. In S. K. Abell & N. G. Lederman (Eds.), *Handbook of Research on Science Education*, 729 – 780. Lawrence Erlbaum Associates, Mahwah, NJ

Roth, G., & Weinstock, M. (2013). Teachers' epistemological beliefs as an antecedent of autonomy-supportive teaching. *Motivation and Emotion, 37*(3), 402-412

Schwartz, R., & Lederman, N. (2008). What Scientists Say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education, 30*(6), 727-771

Taber, K. S. (2008). Towards a Curricular Model of the Nature of Science. *Science & Education, 17*(2-3), 179-218

Taber, K. S. (2010). Straw Men and False Dichotomies: Overcoming Philosophical Confusion in Chemical Education. *Journal of Chemical Education, 87*(5), 552-558

Topcu, M. S. (2013). Preservice Teachers' Epistemological Beliefs in Physics, Chemistry and Biology: A Mixed Study. *International Journal of Science and Mathematics Education, 11*(2), 433-458

Treagust, D. F., Chittleborough, G. D., & Mamiala, T. L. (2004). Students' Understanding of the Descriptive and Predictive Nature of Teaching Models in Organic Chemistry. *Research in Science Education, 34*(1), 1-20

Turner, S., & Sullenger, K. (1999). Kuhn in the Classroom, Lakatos in the Lab: Science Educators Confront the Nature-of-Science Debate. *Science, Technology, & Human Values, 24*(1), 5-30

Van Der Valk, T., Van Driel, J. H., & De Vos, W. (2007). Common Characteristics of Models in Present-day Scientific Practice. *Research in Science Education, 37*(4), 469-488

Van Driel J. H., & Verloop, N. (1999). Teachers' knowledge of models and modelling in science. *International Journal of Science Education, 21*(11), 1141-1153

Vásquez-Alonso, Á., García-Carmona, A., Manassero-Mas, M. A., & Bennàssar-Roig, A. (2013). Science Teachers' Thinking About the Nature of Science : A New Methodological Approach to Its Assessment. *Research in Science Education, 43*(2), 781-808

Vernant, J.-P. (2007). *Les origines de la pensée grecque* (10thedition). Quadriges, Presses Universitaires de France, Paris

Wan, Z. H., Wong, S. L., & Zhan, Y. (2013) Teaching Nature of Science to Preservice Science Teachers: A Phenomenographic Study of Chinese Teacher Educators' Conceptions. *Science & Education, 22*(10), 2593-2619

Wong, S. L., & Hodson, D. (2009). From the Horse's Mouth: What Scientists Say About Scientific Investigation and Scientific Knowledge. *Science Education, 93*(1), 109-130