Myint Swe Khine *Editor*

Advances in Nature of Science Research

Concepts and Methodologies

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Foreword by Richard K. Coll

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Foreword

Interest in, and debate about, the Nature of Science (NoS) is so prevalent nowadays it is easy to forget that education research and scholarly debate about the NoS has persisted for more than 50 years. Despite this NoS is, if anything, increasing in importance, because knowledge of NoS is necessary to become scientifically literate. In my view NoS and scientific literacy are *the* science education issues of our time because of the impact of science on everyday life. Like it or not, science impacts upon the lives of us all, in sometimes alarming ways. This latter observation offers insights into public unease about science and the use to which it is put. I suggest then that each and every citizen needs to understand NoS at some level, and this should be a key output of science education. This book captures contemporary debate about NoS by world experts. It is highly topical and refreshingly challenging in its approach, yet remarkably readable. It is far more than a critical review of the "state of the art" for NoS. The authors challenge our preconceptions about NoS, and challenge us to address our teaching of NoS. The scope of the book is impressive. More impressive still is the synthesis of these ideas which results in a holistic picture of the NoS. To provide us with a comprehensive picture of NoS is one thing; to understand how we might teach NoS is another matter entirely. Modern science teachers get told this or that issue is so very important. All too frequently there is little guidance as to how one might incorporate topics of NoS or scientific literacy into an already crowded curriculum. This book provides researchers and teachers with genuine insights as to current issues in teaching NoS, and consolidates contemporary thinking about NoS. It thus helps us understand NoS in a highly sophisticated way and gives a sound steer as to how we can use this understanding in our teaching practice.

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Part I
Conceptual Issues in the Nature of Science Research

Chapter 1
Changing the Focus: From Nature of Science (NOS) to Features of Science (FOS)

Michael R. Matthews

There has been a long tradition advocating the cultural, educational, personal and scientific benefits of infusing the history and philosophy of science, into science programmes and curriculum – or in current terms, of teaching about the nature of science (NOS) while teaching science. In the nineteenth century, the central figures were William Whewell (1854), Thomas Huxley (1885/1964) and Ernst Mach (1886/1986). In the early decades of the twentieth century John Dewey (1910, 1916) in the United States and Fredrick Westaway (1919/1937, 1929) in the United Kingdom were central figures. In the Anglo-American world, the tradition was continued by Joseph Schwab in the 1940s and 1950s (Schwab, 1949, 1958); by Leo Klopfer (1969) and James Robinson (1968) in the 1960s; by Jim Rutherford (1972), Gerald Holton (1975, 1978), Robert Cohen (1975) and Michael Martin (1972, 1974) in the 1970s.[1]

In the past three decades a number of science educators have extended this tradition. Perhaps the most prominent have been Derek Hodson (1986, 1988, 2008, 2009), Richard Duschl (1985, 1990, 1994) and Michael Matthews (Matthews, 1992, 1994, 1998, 2000, 2009). The International History, Philosophy and Science Teaching Group, through its conferences held biennially since 1989 and associated journal *Science & Education*, have contributed a great deal to this research tradition.

As well as advocacy there has been a mushrooming of empirical studies relating to NOS matters – determining NOS views held by scientists, teachers and representative historians and philosophers; determining the optimal teacher and classroom conditions for most effective NOS teaching; ascertaining the connections between learning NOS and learning science content; developing valid, reliable and efficient tests to measure NOS learning; and so on. Here the work of Norman Lederman and his students have had a particular impact.[2]

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[1] I have surveyed and commented on this history in Matthews (1994, Chaps. 4, 5).

[2] See Lederman (1986, 1992, 2004, 2007) and contributions to Flick and Lederman (2004).

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Science is a human and thus historically embedded truth-seeking enterprise that has many features: cognitive, social, commercial, cultural, political, structural, ethical, psychological, etc. All of these features are worthy of study by science students as well as by disciplinary specialists; and different of them come into clearer focus when considering different sciences, and when considering different aspects of the history, achievements and practice of the different sciences. Some of the features are shared to a large degree with other knowledge-acquiring enterprises, some are shared to a limited degree, and some are not shared at all. Given these characteristics of science, it is useful to understand NOS not as some list of necessary and sufficient conditions for a practice to be scientific, but rather as something that, following Wittgenstein's terminology, identifies a 'family resemblance' of features that warrant different enterprises being called scientific.[3]

This essay recommends a change of terminology and research focus from the essentialist and epistemologically focussed 'Nature of Science' (NOS) to a more relaxed, contextual and heterogeneous 'Features of Science' (FOS). Such a change of terminology and focus avoids the following philosophical and educational pitfalls that have been associated with a good deal of recent NOS research:

(1) The confused jumbling together of epistemological, sociological, psychological, ethical, commercial and philosophical features into a single NOS list.
(2) The privileging of one side of what are contentious and much-debated arguments about the methodology or 'nature' of science.
(3) The assumption of particular solutions of the demarcation dispute.
(4) The assumption that NOS learning can be judged and assessed by students' capacity to identify some number of declarative statements about NOS.

William Whewell: A Precursor to Contemporary NOS Debates

In 1854 the formidable English scientist, philosopher, historian, theologian and moralist William Whewell gave a lecture in Leeds to the Royal Institution of Great Britain on the topic of 'On the Influence of the History of Science upon Intellectual Education' (Whewell, 1854). He prepared the ground for his particular argument by saying

> As the best sciences which the ancient world framed supplied the best elements of intellectual education up to modern times; so the grand step by which, in modern times, science has sprung up into a magnitude and majesty far superior to her ancient dimensions, should exercise its influence upon modern education, and contribute its proper result to modern intellectual culture. (Whewell, 1854, p. 242)

In the lecture he provided passionate argument for the inclusion of NOS (now called) into all liberal education, saying

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[3] This point has been persuasively argued by Gürol Irzik and Robert Nola (2011).

> . . .in the History of Science we see the infinite variety of nature; of mental, no less than bodily nature; of the intellectual as well as of the sensible world.. . .the history of science. . .*may* do, and carefully studied, *must* do, much to promote that due apprehension and appreciation of inductive discovery; and inductive discovery, now that the process has been going on with immense vigour in the nations of Europe for the last three hundred years, ought, we venture to say, to form a distinct and prominent part of the intellectual education of the youth of those nations. (Whewell, 1854, pp. 248–249)

Whewell believed that the history of science was indispensible for understanding 'intellectual culture' more generally, by which he meant the processes of knowledge creation or epistemology. One hundred and more years before Karl Popper, Imre Lakatos and Thomas Kuhn made the view popular, Whewell argued that philosophy of science has to be informed by history of science. In Lakatos's words,

> Philosophy of science without history of science is empty; history of science without philosophy of science is blind. (Lakatos, 1978, p. 102)

Whewell's point is worth drawing attention to, as so much NOS discussion in science education goes on in direct violation of it. NOS is frequently taught without reference to history, and is not informed by history. Unfortunately teachers wishing to convey something of NOS do so by having students 'reflect on', 'brainstorm' or 'discuss' their own classroom activities or investigations as if this was the window onto science.

It was from this conviction that Whewell's monumental three-volume *History of the Inductive Sciences* (Whewell, 1837) informed his equally monumental *Philosophy of the Inductive Sciences, Founded upon Their History* (Whewell, 1840).[4] A source of some confusion is that, despite the title of his books, Whewell was not an inductivist; he did not think that the history of science displayed an inductive/empiricist methodology as currently understood. On the contrary as he famously said in his *History* 'There is a mask of theory over the whole face of Nature'. It was from such a 'theory first' or hypothetico-deductive position that in 1849 he criticized John Stuart Mill's hugely popular and influential *A System of Logic* (Mill, 1843) that had been published a few years earlier and after his own two treatises (Whewell, 1849).[5]

Whewell also expressed two concerns that have occupied much contemporary NOS research when he went on to ask

> How is such a culture to be effected? And also, how are we to judge whether it has been effected? (Whewell, 1854, p. 249)

Whewell was, in contemporary terms, asking: How can NOS best be taught? And, how can NOS learning best be assessed? Educators and researchers are still asking and answering these questions.

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[4] An accessible source for some of Whewell's historical and philosophical studies is Elkana (1984). This includes selections from his *Bridgewater Treatises* on natural theology.

[5] On this, see Elkana (1984, Chap xxii), Laudan (1981) and Yeo (1993).

NOS in Contemporary Curricula

Contemporary educational concern with teaching NOS (broadly construed) can be dated from the 1980s and can be seen in numerous US, UK, Canadian, Turkish, Greek and other national and provincial government reports and curricula (McComas & Olson, 1998). This concern with NOS is perhaps most clearly seen in affirmations of the American Association for the Advancement of Science, especially its landmark 1989 publication *Science for All Americans* (AAAS, 1989) and its 1990 *The Liberal Art of Science* (AAAS, 1990). The latter stated that

> The teaching of science must explore the interplay between science and the intellectual and cultural traditions in which it is firmly embedded. Science has a history that can demonstrate the relationship between science and the wider world of ideas and can illuminate contemporary issues. (AAAS, 1990, p. xiv)

This was elaborated in their *Benchmarks for Science Literacy* document (AAAS, 1993). The AAAS believes that learning about science – its history and methodology – will have a positive impact on the thinking of individuals and will consequently enrich society and culture. That is, NOS learning will have a flow-on effect outside the science classroom. This was, as we will see, an essential belief that the Enlightenment philosophers and educators held about instruction in science or ‘natural philosophy’.

The expectations of the AAAS found their way through to the *US National Science Education Standards* which were drawn up by the National Research Council (whose members were drawn from the councils of the National Academy of Sciences, National Academy of Engineering and the Institute of Medicine). The *Standards* have a separate content strand devoted to ‘History and Nature of Science Standards’ (NRC, 1996).

In the United Kingdom there has been a longer tradition of recognising the importance of NOS learning, broadly construed, in science teaching. Fredrick Westaway, an ‘Her Majesty’s Inspector of Schools’ in the United Kingdom in the 1920s who also authored substantial books on history of science and philosophy of science, wrote that a successful science teacher is one who

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

The most recent concerted UK effort to teach NOS material is the new optional Upper Level *Perspectives on Science* course for England and Wales (Swinbank & Taylor, 2007). The course has four parts:

Pt. 1 Researching the history of science
Pt. 2 Discussing ethical issues in science

Pt. 3 Thinking philosophically about science
Pt. 4 Carrying out a research project

The textbook for this course, on its opening page, says

> *Perspectives on Science* is designed to help you address historical, ethical and philosophical questions relating to science. It won't provide easy answers, but it will help you to develop skills of research and argument, to analyse what other people say and write, to clarify your own thinking and to make a case for your own point of view. (Swinbank & Taylor, 2007, p. vii)

The Philosophy section begins with about 16 pages outlining fairly standard matters in philosophy of science – nature of science, induction, falsifiability, paradigms, revolutions, truth, realism, relativism, etc. Importantly, the book then introduces the subject of 'Growing your own philosophy of science' by saying

> Having learned something about some of the central ideas and questions within the philosophy of science, you are now in a position to evaluate the viewpoints of some scientists who were asked to describe how they viewed science. The aim here is to use these ideas as a springboard to develop and support your own thinking. (Swinbank & Taylor, 2007, p. 149)

The Enlightenment Tradition

To better understand reasons for contemporary advocacy of history and philosophy, or NOS, in science teaching, and current concern to have empirical studies of the efficacy of teaching NOS, it is informative to go back to the origins of these concerns in the European Enlightenment.[6] The Enlightenment philosophers – Locke, Voltaire, D'Alembert, Condorcet, Hume; and a little later Franklin, Priestley, Jefferson and Kant – were inspired by the dramatic achievements of the New Science of the seventeenth century. The seventeenth-century Scientific Revolution was the seed that produced the eighteenth-century Enlightenment plant. The scientific accomplishments in mechanics, astronomy, horology, medicine and other fields are well known. These 'natural philosophy' endeavours were institutionalised with the establishment of The Royal Society in England (1660) and the *Académie Royal des Sciences* in France (1666).[7]

David Hume, in his *History of England,* wrote that Newton was 'the greatest and rarest genius that ever rose for the ornament and instruction of the species' (Hume, 1754–62/1828, Vol. IV, p. 434). This was of course one Englishman writing about another Englishman, but nevertheless Hume well expressed the general view of Newton's preeminence in seventeenth-century science. Newton famously said in a letter to Robert Hooke (5th February, 1676), 'If I have seen a little further

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[6] Some excellent recent books on the Enlightenment include Dupré (2004), Hankins (1985), Himmelfarb (2004), Israel (2001) and Porter (2000).

[7] One of numerous guides to the achievements of the Scientific Revolution is Gribbin (2002, Book 2).

it is by standing on the shoulders of Giants'. Although Newton did so stand, and there were many giants to stand on, including Galileo, Kepler and Huygens, clearly his *Principia* (Newton, 1713/1934) and *Optics* (Newton, 1730/1979) provided the foundation of modern science and the inspiration for the Enlightenment. Newton's self-styled 'under-labourer', John Locke, wrote five major Enlightenment texts in the decade after the publication of the *Principia* (Locke, 1689/1924, 1689/1983, 1690/1960, 1693/1996 and 1695/1999).

In the appalling, unhealthy, warring, oppressive, autocratic, social, political, religious and cultural circumstances of seventeenth-century Europe – with its witch crazes, religious wars, heretic burnings, divine-right lords, denial of all free speech, and so on – it was not surprising that many thought that it would be truly wonderful if Newton's scientific achievements might be replicated in fields outside of natural philosophy; if his approach and 'method' could be applied more broadly. It was the hope of many that lessons from the New Science might have flow-on effects for culture, society and personal life. Newton certainly had this view. As he stated it, 'If natural philosophy in all its Parts, by pursuing this Method, shall at length be perfected, the Bounds of Moral Philosophy will be also enlarged' (Newton, 1730/1979, p. 405).

The Enlightenment philosophers held three convictions:

(1) They believed that the method of the new science was the only way of finding out truths about Nature; the methods of the Scholastic natural philosophers were obsolete and of no use.
(2) They thought that the new method had application well beyond the observatory, laboratory and workbench; the new method was useful in the investigation of many social, cultural and even religious questions.
(3) They thought that the method of the new science was not something just to be utilised by the natural philosophers, the scholars or the learned elite. They were committed to education, and the promotion of 'scientific' thinking in the population; they believed in, as one might say, 'Science for All'.

John Dewey, 300 years later, well expressed these Enlightenment hopes when he said

> Scientific method is not just a method which it has been found profitable to pursue in this or that abstruse subject for purely technical reasons. It represents the only method of thinking that has proved fruitful in any subject. (Dewey, 1910, p. 127)

And when, in his justly famous *Democracy and Education*, he wrote

> Our predilection for premature acceptance and assertion, our aversion to suspended judgment, are signs that we tend naturally to cut short the process of testing. We are satisfied with superficial and immediate short-visioned applications. ... Science represents the safeguard of the race against these natural propensities and the evils which flow from them. ... It is artificial (an acquired art), not spontaneous; learned, not native. To this fact is due the unique, the invaluable place of science in education. (Dewey, 1916, p. 189)

Some Problems with Contemporary Empirical NOS Research: The Lederman Programme

Many individuals and groups in science education have researched factors impinging on the teaching and learning of NOS: What is taught? How it is taught? What is learned? How it is best learnt? What are the different outcomes between explicit or implicit instruction? etc.[8] This research has achieved much, but suffers because of 'soft focus' and ambiguous writing at critical points where important philosophical issues are at play. The field of NOS research in science education is yet another example where more cooperation between science educators, historians and philosophers would considerably improve the usefulness and quality of published work.

At the outset it is important to appreciate that science educators have typically taken a broad, and fairly relaxed, view of the nature of science; this 'relaxed' position bears upon the validity of test instruments and of informed assessment of NOS learning.[9] In many cases what are labelled 'NOS factors' by test designers and education researchers would be thought of as just 'features of science' by philosophers; not necessarily things that especially distinguish science or, in essentialist terms, pertain to the nature or essence of science.

This section deals with the work of just one representative group of science education researchers, the group that formed around Norman Lederman.[10] This group is chosen because they have been working for two decades or so, and probably are the most cited and the most influential authors in the field. Their definition of NOS is characteristically catholic:

> Typically, NOS refers to the epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development. (Lederman, Abd-el-Khalick, Bell, & Schwartz, 2002, p. 498)

It is noteworthy that in this definition both epistemological *and* sociological aspects of science are subsumed under the NOS umbrella. This rings philosophical alarm bells; it should alone be sufficient to suggest a change from 'nature of science' to 'features of science'. There may well be some limits on the epistemology or methodology of science, but clearly there will be no such limits on the sociology

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[8] See contributions to special issues of *Science & Education* (vol. 6 no. 4 1997, vol. 7 no. 6 1998), McComas (1998), Flick and Lederman (2004). See also the literature reviews in Abd-El-Khalick and Lederman (2000) and Lederman (2007).

[9] For a critical account of instruments used for NOS assessment from the 1950s to the present, see Lederman, Wade and Bell (1998).

[10] Norman Lederman, now professor of science education at the Chicago Institute of Technology, was formerly at Oregon State University. Among his many publications see especially Lederman (1992, 2004). His original Oregon State students included Fouad Abd-El-Khalick, Renee Schwartz, Valarie Akerson and Randy Bell – all of whom have published widely in this field.

of science; the latter will cover politics, commerce, education, professional structures, advertising, and whatever else those studying science as a historical process might have an interest in.

The 'Lederman Seven'

The Lederman group maintains that 'no consensus presently exists among philosophers of science, historians of science, scientists, and science educators on a specific definition for NOS' (Lederman, 2004, p. 303). Although recognising no across-the-board consensus on NOS, the group does claim that there is sufficient consensus on central matters for the purposes of NOS instruction in K-12 classes. The group has elaborated and defended seven elements of NOS (the 'Lederman Seven' as they might be called) that they believe fulfil the criteria of

(i) accessibility to school students;
(ii) wide enough agreement among historians and philosophers; and
(iii) being useful for citizens to know.[11]

The seven elements are as follows:

1. The *empirical nature of science*, where they recognised that although empirical, scientists do not have direct access to most natural phenomena. It is claimed that 'Students should be able to distinguish between observation and inference ... An understanding of the crucial distinction between observation and inference is a precursor to making sense of a multitude of inferential and theoretical entities and terms that inhabit the worlds of science'. (Lederman et al., 2002, p. 500)
2. *Scientific theories and laws*, where they hold that 'laws are descriptive statements of relationships among observable phenomena... Theories by contrast are inferred explanations for observed phenomena or regularities in those phenomena. ... Theories and laws are different kinds of knowledge and one does not become the other'. (Lederman et al., 2002, p. 500)
3. The *creative and imaginative nature of scientific knowledge*, where they hold that 'science is empirical ... Nonetheless, generating scientific knowledge also involves human imagination and creativity. Science ... is not a lifeless, entirely rational and orderly activity. ...scientific entities, such as atoms and species are functional theoretical models rather than copies of reality'. (Lederman et al., 2002, p. 500)
4. The *theory-laden nature of scientific knowledge*, where it is held that 'Scientists' theoretical and disciplinary commitments, beliefs, prior knowledge, training,

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[11] The list is articulated and defended in, among other places, Lederman et al. (2002, 499–502), Lederman (2004, 303–308), Schwartz and Lederman (2008, 745–762).

experiences, and expectations actually influence their work. All these background factors form a mindset that affects the problems scientists investigate and how they conduct their investigations'. (Lederman et al., 2002, p. 501)

5. The *social and cultural embeddedness of scientific knowledge*, where it is held that 'Science as a human enterprise is practiced in the context of a larger culture and its practitioners are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded'. (Lederman et al., 2002, p. 501)
6. The *myth of scientific method*, where it is held that 'There is no single scientific method that would guarantee the development of infallible knowledge... and no single sequence of activities ... that will unerringly lead [scientists] to functional or valid solutions or answers'. (Lederman et al., 2002, p. 502)
7. The *tentative nature of scientific knowledge*, where it is maintained that 'Scientific knowledge, although reliable and durable, is never absolute or certain. This knowledge, including facts, theories, and laws, is subject to change'. (Lederman et al., 2002, p. 502)

This list has functioned widely in science education as a NOS checklist; it appears on classroom walls somewhat like the Seven NOS Commandments; and it informs the group's hugely popular series of VNOS (Views of Nature of Science) tests which are used in scores of published research papers to measure effectiveness of NOS teaching (Lederman et al., 2002) and degrees of NOS understanding (Flick & Lederman, 2004, Chap. IV, Schwartz & Lederman, 2008, Chen, 2006). The positive side of the list is that it puts NOS into classrooms; it provides researchers with an instrument for measurement of NOS learning; and it can give teachers and students some NOS matters to think through and become more knowledgeable about. The negative side is that the list can, despite the wishes of its creators, function as a mantra, as a catechism, as yet another something to be learnt. Instead of teachers and students reading, analysing, and coming to their own views about NOS matters, the list often short-circuits all of this. And in as much as it does so, it is directly antithetical to the very goals of thoughtfulness and critical thinking that most consider the reason for having NOS (or HPS) in the curriculum.

As an example of the hurdles that attend an NOS focus, consider the much-written on claim made by the philosopher Larry Laudan that it is impossible to even demarcate science from other intellectual pursuits. Laudan maintains that

> From Plato to Popper, philosophers have sought to identify those epistemic features which mark off science from other sorts of beliefs and activity. Nonetheless, it seems pretty clear that philosophy has largely failed to deliver the relevant goods. Whatever the specific strengths and deficiencies of the numerous well-known efforts at demarcation. . .it is probably fair to say that there is no demarcation line between science and non-science, or between science and pseudo-science, which would win assent from a majority of philosophers. (Laudan, 1996, p. 210)

If Laudan is correct, then the whole prospect of identifying, much less, itemising some NOS list is otiose.[12] But a focus on FOS avoids this hurdle. The possibility of demarcation is just one of numerous features of science that can engage teachers and students. The demarcation question becomes a subject for inquiry, not a catechismal matter. An FOS focus leaves open the demarcation question; a NOS focus presupposes a particular answer to it.

The Devil Is in the Detail: The Need for Philosophical Articulation

The seven features of science, or NOS elements, clearly need to be much more philosophically and historically refined and developed in order to be useful to teachers and students. This is not just the obvious point that when seven matters of considerable philosophical subtlety, and with long traditions of debate behind them, are dealt with in a few pages, then they will need to be further elaborated, rather it is the more serious claim that at crucial points there is ambiguity that mitigates the list's usefulness as curricular objectives, assessment criteria, and as goals of science teacher education courses.

For instance consider the first item on the list – the empirical basis of science. There are two large problems that this label glosses over: First, the ontological status of theoretical entities in science; second, the role of abstraction and idealisation in science.

First, in discussing the empirical nature of science, it is maintained that there is wide enough agreement on the 'existence of an objective reality, for example, as compared to phenomenal realities' (Lederman, 2004, p. 303). This is quite so, but the serious debate among philosophers is not the reality of the world, but the reality of explanatory entities proposed in scientific theories. This debate between realists on the one hand, and empiricists, constructivists and instrumentalists on the other has gone on since Aristotle's time.

Aristotle maintained that the crystalline spheres in which the planets were supposedly embedded were a real existing mechanism that kept planets in their regular circular orbits, his empiricist rivals held that the spheres were merely mental connivances to give order to experience, they had no ontological reality. The debate was famously replayed when Cardinal Bellarmine urged Galileo to adopt an instrumentalist view of Copernican heliocentric astronomy – that heliocentrism was useful for astronomical calculations, but it was not actually how the solar system was arranged.[13]

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[12] Laudan first made the claim in his 'Demise of the Demarcation Problem' (Laudan, 1983). A recent survey of the ensuing debate, and refutation of the claim, is provided by Robert Pennock (2011).

[13] The classic treatment of the ancient and medieval debates about 'saving appearances' as the goal of natural philosophy is Duhem (1908/1969).

The debate replayed when Bishop Berkeley criticised Newton's realist account of force, saying that 'Force, gravity, attraction and similar terms are convenient for purposes of reasoning and for computations of motion and of moving bodies, but not for the understanding of the nature of motion itself' (Berkeley, 1721/1901, p. 506).[14] And it played again when the positivist Ernst Mach criticised realist interpretations of atomic theory, saying that those theorists had 'done more than science, whose aim is facts, requires of him – and this work of superogation is an evil' (Mach, 1872/1911, p. 57).

The debate between realist and empiricist or instrumentalist interpretations of the theoretical entities postulated by scientific theories was central to disputes in quantum mechanics (Bunge, 2003). And has recently surfaced in Chemistry over the reality or otherwise of chemical bonds: Are there really covalent and ionic bonds or is there just macro-bonding behaviours for which postulation of micro unseen bonds is just a convenient shorthand for regularities at the macro level? (Vollmer, 2003).[15]

Throughout the 2,500 years since Aristotle's postulation of crystalline spheres, it has not been the existence of the world that has been doubted – Bellarmine, Berkeley, Mach and Bohr did not doubt the existence of objects, just the unseen entities and mechanisms that the science of their time was postulating to explain the visible, macro or phenomenal behaviour of the objects. This whole history is removed from science education discussion when the first element in the Lederman list simply says that 'science has an empirical base'. Well yes, it does, but the issue is more complex; and as with many things, the devil is in the detail. It might be said that students cannot comprehend the detail, but this is an empirical matter; certainly teachers can and should comprehend the detail.

The Lederman group are realists about the world, but it is very unclear whether they are realists about science's theoretical entities – the very issue on which the realist/instrumentalist (constructivist) debate has hinged. It is not the reality of the world that teachers need guidance about, it is the reality or otherwise of entities postulated in scientific theories. Lederman rhetorically asks, 'can it be said that a student truly understands the concept of a gene if he/she does not realize that a "gene" is a construct invented to explain experimental results?' (Lederman, 2004, p. 314) And repeats the question by asking, 'Does the student who views genes as possessing physical existence analogous to pearls on a necklace possess an in-depth understanding of the concept?' (ibid.) The point is repeated when it is asked, 'Does the student who is unaware that the atom (as pictured in books) is a scientific model used to explain the behavior of matter and that it has not been directly observed have an in-depth understanding of the atom?' (ibid.)

These questions mask serious and misleading ambiguity concerning the existence of genes and atoms. At first reading, the questions seem to suggest an instrumentalist, non-realist view of these central explanatory entities; they appear to 'in

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[14] For Berkeley's positivist critique of Newtonian theory, see Popper (1953/1963).

[15] For the outlines of this debate, and a guide to some of the literature, see Matthews (1994, Chap. 8).

principle' not exist, but be merely a human 'construct'. What if the student thinks of genes not as pearls on a necklace, but links in a necklace chain: Is this sufficient sophistication to rate as high NOS understanding? Or what if a student thinks of atoms not as pictured in the textbook, but as some sort of micro particle: Is this sufficient to rate as high NOS understanding? The crucial NOS issue is whether genes and atoms exist at all, exist in principle, not whether any particular picture of them is correct. Once we grant in-principle existence, we can be reasonably relaxed about any particular picture; this is just a matter for good science education to fill in. But Lederman is silent about whether it is in-principle existence or just some particular existence – pearl-like genes, or red and green atoms – that is being denied.

The same ambiguity can be seen when another member of the group, Fouad Abd-El-Khalick, recognises that 'The world of science is inhabited by a multitude of theoretical entities, such as atoms, photons, magnetic fields, and gravitational forces to name only a few'. All realists recognise that the entities listed are both theoretical and central to science, but Abd-El-Khalick proceeds to say that these are 'functional theoretical models rather than faithful copies of "reality" ' (Abd-El-Khalick, 2004, pp. 409, 410). Here again is the crucial ambiguity. One wonders why 'reality' was put in scare quotes as this introduces some element of doubt about reality itself, but this doubt can be left aside for the moment as he is a realist about reality. But more importantly, functional theoretical models can either have a reference (denote something existing) or merely link observables in a, usually, mathematical way that has no ontological import. Abd-El-Khalick's claim is ambiguous at the crucial point of whether the listed theoretical entities are non-existing 'functional theoretical models' in virtue of them not being 'faithful copies of reality' or in virtue of their very nature.

This is a re-phrasing of the long-discussed distinction between hypothetical constructs (which in principle can have existence, although they may, as a matter of fact not exist; or not exist with the properties attributed to them) and intervening variables (which in principle have no existence, but merely link observables).[16] In the nineteenth century, caloric and Neptune were hypothetical constructs; one turned out to have existence, the other did not. The notion of 'average-family number' when applied to societies functions as an intervening variable: there is no suggestion that any particular family has 3.7 members; the latter is not meant to copy, faithfully or otherwise, any particular reality. The crucial question is whether atoms, photons, magnetic fields, gravitational forces are like average-family numbers? Bellarmine, Berkeley, Mach and Bohr would say 'yes'; it is simply unclear if Abd-El-Khalick agrees with them or not. If attention had been paid to spelling out the meaning of 'functional theoretical model', this ambiguity would be removed.

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[16] A classic discussion of the difference between hypothetical constructs (that in principle have existence) and intervening variables (that in principle do not have existence) is Meehl and MacCorquodale (1948). Clarity on this issue is of absolute importance in social science: Is 'intelligence' to be understood as a hypothetical construct or an intervening variable? Rivers of ink have been spilt because researchers have not clarified the kind of thing they are looking for.

At a surface reading, it would seem that the Lederman group are empiricists and constructivists about theoretical entities in science. If so, this is a mistake, and is not the message about NOS that science teachers should convey. The mistake is not so much the assumption of one philosophical side, constructivism, in this debate but rather giving the impression that there is no debate or no alternative position that can and has been adopted – the realist position. Once again, a concentration on *the* NOS rather than open discussion and inquiry about FOS leads to this mistake.

The second problem with the Lederman Group's 'empirical basis' characterisation is that it disguises, if not completely distorts, the non-empirical component of science. The very process of abstraction, and idealisation, is the beginning of modern science. It is an ability to see the forest, and not just the trees. Consider Galileo's 'thousands of swings' of the pendulum. He clearly saw no such thing, it is a claim about what he would see if the impediments to pendulum motion were removed (Matthews, 2000). Similarly Newton did not see inertial bodies continuing to move in a straight line indefinitely. This is what he would have seen if all resistance were removed. Fermi and Bernardini, in their biography of Galileo, emphasise this innovation:

> In formulating the 'Law of Inertia' the abstraction consisted of imagining the motion of a body on which no force was acting and which, in particular, would be free of any sort of friction. This abstraction was not easy, because it was friction itself that for thousands of years had kept hidden the simplicity and validity of the laws of motion. In other words, friction is an essential element in all human experience; our intuition is dominated by friction; men can move around because of friction; because of friction they can grasp objects with their hands, they can weave fabrics, build cars, houses, etc. To see the essence of motion beyond the complications of friction indeed required a great insight. (Fermi & Bernardini, 1961, p. 116)

The point of this drawn-out discussion of the first item on the Lederman list is to indicate that such a claim about the empirical basis, and the role of inference, needs to be elaborated at a much more sophisticated level in order to both be useful and to avoid massive misunderstandings of the scientific endeavour. Further with just the slightest elaboration, the more or less uncontroversial and mundane claim – that science has an empirical base – can be transformed into an engaging inquiry that can link teachers and students with a central philosophical argument in the history of philosophy, namely realist or instrumentalist interpretation of scientific theory, a debate to which the greatest minds can be found on either side. It is not a simple, 'open and shut' matter that can be reduced to a declarative list.

The same kind of argument can be mounted against each of the other items on the Lederman list. A general point is that such necessary elaboration depends upon teachers having some competence or at least familiarity with the history and philosophy of science, and notoriously such training is absent from teacher-education programmes.

For instance the fourth claim is that 'Scientific knowledge is subjective or theory-laden'. Again, the claim is ambiguous: one can say both 'yes' and 'no'. First to acknowledge that some claim is theory-laden is not equivalent to saying it is subjective in the usual psychological meaning of the term. But the meaning being used by the Lederman group is simply ambiguous. For instance Lederman says that 'I am not advocating that scientists be subjective' (Lederman, 2004, p. 306). Here 'subjective' must be the everyday psychological sense of the term. But previously we have been dealing with, what one might call, 'philosophical subjectivity', as it has been stated that subjectivity is equivalent to theory-ladeness, and that 'subjectivity is unavoidable' (ibid.). Clearly all science is theory-laden, as Lederman rightly points out; but if so, then scientists have to be subjective (as in philosophical subjectivity), whether it is advocated or not advocated. But this is entirely different from psychological subjectivity.

The entire history of modern science is an effort to take out, or minimise, the psychological subjectivity in measurement and explanation – beginning with the earliest use of measuring instruments in order to get inter-subjective agreement about weight, length, time, etc. Galileo's creation of the pulsilogium so as to be able to objectively measure pulse rate for medical diagnosis is one such example. The entirely subjective 'fast', 'medium', 'slow' was replaced by the length of a pendulum beating in time with the patient's pulse.[17] The force of the fourth claim trades entirely upon an ambiguity, which is unfortunate in something so widely used as a check-list of NOS understanding.

The fifth claim is that science is embedded in culture, that it 'affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded' (Lederman, 2004, p. 306). It is important that this be recognised, but again the devil is in the detail, and the detail is not provided. We know that the cultures of Nazism (Beyerchen, 1977), Stalinism (Graham, 1973, Birstein, 2001), Islam (Hoodbhoy, 1991) and Hinduism (Nanda, 2003) to take just some examples, dramatically affected scientific investigation wherever they were powerful enough to do so. And of course the impact, for good and bad, of Christian culture, beliefs and authorities on science is well documented (Lindberg & Numbers, 1986). Clearly indigenous sciences are affected by the worldviews and social structures in which they are practised.

All commentators on the European scientific revolution recognise that the blossoming of the New Science of Galileo, Huygens, Newton, Boyle, etc, was dependent on, though not caused by, social and cultural circumstances of seventeenth century Europe.[18] Counterwise, scholars have tried to identify the absence of such circumstances in China at the time to account for why there was no comparable scientific revolution in China (Needham & Ling, 1954–65). In a famous and contentious study, Paul Forman attempted to provide a causal link between the culture

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[17] See Matthews (2000, pp. 88–89).

[18] The classic statement of this position, but with the causal twist, is Boris Hessen's 1931 *The Social and Economic Roots of Newton's 'Principia'*. For Hessen's text and commentary see Freudenthal and McLaughlin (2009). One well-known elaboration of the thesis, in the causal direction, is Freudenthal (1986).

of Weimar Germany and the creation of indeterminate quantum theory (Forman, 1971).

The sociological and historical facts of the matter are not in dispute – science depends upon technology, mathematics, communications, money, education, philosophy and culture more broadly – and it is useful for students and teachers to be reminded of all this and to be given examples. But for this fact to be truly useful, and not just a sort of anthropological observation, teachers (and their pupils) need to be engaged in or inquire about issues such as separating benign from adverse effects of culture; distinguishing good from bad science; identifying internal and external factors in scientific development; trying to determine just how analogous are Western and indigenous science; and so on. But the Lederman group is silent on these ultimately normative matters.

We are told just that although Western Science dominates North American schools, there 'exist other analogous sciences (e.g., indigenous science) in other parts of the world' (Lederman, 2004, p. 307). The ambiguity here over 'analogous' means that this item on the list gives no direction to teachers, either in cultures that are resistant to Western Science, or in multicultural situations. It is a too-easy step to move from this anthropological claim to the educational conclusion that where other analogous sciences exist, then they should be taught.[19] The group does say that NOS means, among other things, identifying the 'values and beliefs inherent to scientific knowledge and its development' (Lederman, 2004, p. 303). The use of the word 'inherent' suggests that effort will be made to spell out just what is and is not inherent to science, and this would be the occasion to comment on benign and adverse impacts of culture on science; but the matter is not addressed. This can be a good thing, if teachers and students are meant to work out their own answer, but the list is meant to function as a characterisation of the nature of science, and further is to be used in assessing competence in NOS understanding, for these purposes more elaboration is needed.

Item seven on the Lederman NOS list is a claim about the 'tentativeness' of scientific knowledge. We are told that 'tentativeness in science does not only arise from the fact that scientific knowledge is inferential, creative, and socially and culturally embedded' but 'There are also compelling logical arguments that lend credence to the notion of tentativeness in science' (Lederman, 2004, p. 307). Again, as with all the other items on the list, one can say 'yes' or 'no' depending on how the claim is interpreted. First, contrary to what is stated, absolutely nothing follows about tentativeness from the recognition that knowledge is 'inferential, creative, and socially and culturally embedded' unless one adds a premiss to the effect that, by definition, knowledge so characterised is tentative. But, without argument, there is no need to add such a premiss. If we infer a *particular* cause for some effect, this might be a tentative belief, but to infer that there is a cause, is not tentative in the same way.

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[19] For a philosophically sophisticated discussion of some of the issues, see Nola and Irzik (2006).

Features of Science (FOS)

There are seven items on the Lederman NOS list:

(1) Empirical basis
(2) Scientific theories and laws
(3) Creativity
(4) Theory dependence
(5) Cultural embeddedness
(6) Scientific method
(7) Tentativeness

I have been arguing that these should better be thought of as different features of science (FOS) to be elaborated, discussed and inquired about, rather than nature of science (NOS) items to somehow be learnt and assessed. Each of these features has been richly written about by philosophers, historians and others – as has been indicated above for some on the list. But if they are features of science, then there is no good reason why just those seven features are picked out, and not others of the numerous features – epistemological, historical, psychological, social, technological, economic, etc. – that can be said to characterise scientific endeavour, and that also meet the three criteria of accessibility, consensus and usefulness that the Lederman group additionally utilise to reduce NOS matters to classroom size.

Clearly many other things can be added to the above list. Among philosophers, NOS discussion and debate has traditionally revolved around investigations of the epistemological, methodological, and ontological commitments of science. But there are illuminating, non-philosophical studies of science, such as conducted by historians, cognitive psychologists, sociologists, economists, anthropologists, and numerous other disciplines. The term ‘Science Studies’ encompasses the complete academic spectrum, and all components have useful things to say about different features of science. Just some of the additional topics, issues or questions that can usefully engage science teachers and students might be

(8) *Experimentation*. The long-standing Aristotelian injunction about not interfering with nature if we want to understand her was rejected first by Galileo, with his famous inclined plane experiments conducted so as to understand the phenomena of free fall, then progressively by the other foundation figures of early modern science, most notably Newton with his pendulum experiments in mechanics and his prism manipulations in optics. It was this newly introduced experimentalism that occasioned Kant to remark that

> When Galileo caused balls, the weights of which he had himself previously determined, to roll down an inclined plane; when Torricelli made the air carry a weight which he had calculated beforehand to be equal to that of a definite volume of water . . . a light broke upon all students of nature. They learned that reason has insight only into that which it produces after a plan of its own, and that it must not allow itself to be kept, as it were, in nature’s leading-strings. (Kant, 1787/1933, p. 20)

Historians and philosophers have written a great deal on this topic, and of course it can connect immediately with a more sophisticated understanding of school laboratory work and student experimentation (Chang, 2010; Hodson, 1993, 1996).

(9) *Idealisation*. What is the role, function and status of idealisation in scientific theorising? How are laws about idealised and contrary-to-fact conditions reconciled with claims that laws of nature are about the world? (Nowak, 1980)

Galileo was the first to build idealisation into the investigation of nature, and it was this methodological move that enabled his New Science to emerge from its medieval and Renaissance milieu.[20] What Galileo recognised was that nature's laws were not obvious in nature; they were not given in immediate experience; the laws applied only to idealised circumstances. This employment of idealisation was also in flat contradiction to the long empiricist Aristotelian tradition whereby 'science' was to be about the world as seen and experienced. As Aristotle maintained, 'If we cannot believe our eyes what should be believe?' In contrast, Galileo immediately after proving his famous Law of Parabolic Motion says

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

Of crucial importance was the fact that idealisation, and only idealisation, gave specific direction to experimentation so that students of nature (reason) could mould nature 'after a plan of its own', in Kant's famous words. The decades and centuries of classical mechanics, began by Galileo, were a long process of transforming nature in the image of theory; that is what an experiment was: controlling all variables identified by theory as being irrelevant, and varying the one held responsible for the phenomena.

(10) *Models*. The ubiquity of models in the history and current practice of science is widely recognised, indeed it is difficult to think of science without models: the 'billiard ball', 'plum-pudding' and 'solar system' models of the atom, the electron orbit model for the periodic table, the 'lattice' model of salt structure, the fluid-flow model of electricity, the double-helix model of the chromosome, the 'survival of the fittest' model for population expansion in eco-systems, the particle model of light, the 'big bang' model in cosmology, the '3-body' model for sun–earth–moon interaction, full dinosaur models from bone fragments in palaeontology, the plate-tectonic model in geophysics, the scores of mathematical models in hereditary and population studies, the thousands of mathematical models in economics, engineering, and so on. Any 10 pages of a science textbook might be expected to contain twice that number of models, many in full glossy colour, with state-of-the-art graphics.

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[20] I have argued this claim at some length in Matthews (2000, pp. 245–48).

> In the past half-century historians and philosophers of science have devoted considerable time to documenting and understanding the role of models in science and social science. These studies have led scholars to examine model-related topics such as the nature of scientific theory, the status of hypothesis, the role of metaphor and analogy in scientific explanation, thought experiments in science, and the centrality of idealisation for the articulation, application and testing of models. Mary Hesse's (1953, 1961, 1966) and Rom Harré's (1960) publications were foundational for the contemporary tradition (realist and non-realist) of model-related research, with Hesse's *Models and Analogies in Science* (1966) being of particular importance. Philip Johnson-Laird's book *Mental Models* (1983) was, and still is, enormously influential. He, and associates, provided an explanation for the ubiquity of models in science when they detailed how models were ubiquitous not just in science but in all mental life.
>
> Once more, if models are seen as an important feature of science, then a competent HPS-informed teacher can provide rich materials and questions for class discussion on the topic: How do models relate to the world they model? Is learning the properties of models the same as learning about the world? As with so many FOS questions, there is no uncontested answer, just better informed and better argued answers. A number of rich studies can be seen in the recent special issue of *Science & Education* devoted to the subject – 'Models in Science and in Science Education' (2007, vol. 16 nos. (7–8).

And of course this extended FOS list can simply be extended to include any number of other important and engaging features of science:

(11) Values and Socio-scientific issues
(12) Mathematisation
(13) Technology
(14) Explanation
(15) Worldviews and Religion
(16) Theory choice and rationality
(17) Feminism
(18) Realism and Constructivism

All of these subjects have been extensively written upon, as can be seen by a perusal of any introductory HPS textbook.

Modest Goals for FOS Teaching

We should have modest goals when teaching about FOS. In the opening page of the AAAS *Benchmarks* document it was stated that 'Little is gained by presenting these beliefs to students as dogma. For one thing, such beliefs are subtle' (AAAS, 1993,

p. 5). The same points are made in the UK *Perspectives on Science* course, where it is repeatedly stated that students will gain appreciation of NOS positions and issues, and competence in NOS thinking, rather than declarative knowledge of NOS. It is important to stress these points: First FOS claims should not be presented as dogma, to do so is to confuse education with indoctrination; and second most, if not all, statements about FOS are subtle, and recognition of this subtlety simply depends upon having historical and philosophical (HPS) awareness. Both these points have implications for the very vexed and much-written up topic of the assessment of FOS and NOS learning (Rudge & Howe, 2010).

It is unrealistic to expect students, or trainee teachers, to become competent historians, sociologists or philosophers of science. We should have limited aims in introducing FOS questions in the classroom. Teachers should aim for a more complex understanding of science, not a total, or even a very complex, understanding. Fortunately philosophy does not have to be artificially imported to the science classroom, is not far below the surface in any lesson or textbook. At a most basic level any text or scientific discussion will contain terms such as ‘law’, ‘theory’, ‘model’, ‘explanation’, ‘cause’, ‘truth’, ‘knowledge’, ‘hypothesis’, ‘confirmation’, ‘observation’, ‘evidence’, ‘idealisation’, ‘time’, ‘space’, ‘fields’, ‘species’. Philosophy begins as soon as these common and ubiquitous terms are explained, amplified and discussed.

There is no need to overwhelm students with ‘cutting-edge’ philosophical questions. They have to crawl before they can walk, and walk before they can run. This is no more than commonsensical pedagogical practice. There are numerous low-level philosophical questions that are legitimate FOS questions: What is a scientific explanation? What is a controlled experiment? What is a crucial experiment and are there any? How do models function in science? How much confirmation does a hypothesis require before it is established? Are there ways of evaluating the worth of competing research programmes? Did Newton’s religious belief affect his science? Was Darwin’s ‘damaged book’ analogy a competent rely to critics who pointed to all the evidence that contradicted his evolutionary theory? Was Planck culpable for remaining in Nazi Germany and continuing his scientific research during the war? And so on.

Likewise history is unavoidable. Texts are replete with names such as Galileo, Newton, Boyle, Hooke, Darwin, Mendel, Faraday, Volta, Lavoisier, Dalton, Rutherford, Curie, Bohr, Heisenberg, Einstein, and others. History ‘lite’ begins when teachers, as Westaway was quoted earlier, ‘talk to [students] about the personal equations, the lives, and the work of such’ figures. And encourage students to do their own research on these scientists. History ‘full strength’ begins when the experiments and debates of these figures are reproduced in the classroom; when ‘historical-investigative’ teaching is practised (Kipnis, 1996, 1998).

Other features of science are on daily display in newspapers, TVs and the Internet, where accounts of socio-scientific and techno-value debates about genetics, agro-business, climate change, GM crops, global warming, and so on are constant features. If understanding FOS is embraced as a curricular goal, then well-prepared teachers should be able to elaborate a little on these matters and facilitate useful classroom discussion and learning.

Twelve years ago I wrote

> Science educators should be modest when urging substantive positions in the history and philosophy of science, or in epistemology. . . .Modesty does not entail vapid fence-sitting, but it does entail the recognition that there are usually two, if not more, sides to most serious intellectual questions. And this recognition needs to be intelligently and sensitively translated into classroom practice. (Matthews, 1998, pp. 169–170)

The change of focus from NOS to FOS greatly facilitates this orientation. NOS research has concentrated on the nature of scientific knowledge; FOS includes this, but is also concerned with the processes, institutions and cultural and social contexts in which this knowledge is produced.

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Chapter 2

Perceptual, Attentional, and Cognitive Heuristics That Interact with the Nature of Science to Complicate Public Understanding of Science

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Effective communication of scientific findings is critical to sustaining an informed society that can make the best decisions from the science that it funds and that affects daily life. Yet, despite a scientist's best intentions, attempts to communicate scientific results are often fraught with difficulty. Here, we draw together disparate strands of scholarship to argue that the patterns of perception, attention, and cognition, which guide how humans take in and deal with information, are typically at odds with the demands of processing complex scientific information and with how science produces knowledge. Scientists who hope to impact public understanding will benefit from an awareness of these human patterns, how they interact with understanding the nature of science, and what this means for presenting scientific information to the public.

Gaining the Public's Attention

Gaining and maintaining the public's attention is one of the first challenges a scientist meets when trying to share research findings. In a sea of messages competing for the public's attention, what breaks through and what manages to sustain attention? A growing literature informs how people respond to perceptual stimuli, what information holds salience for them, and how they consciously and unconsciously allocate their attention. Findings based on research from visual and auditory perception and the design of our perceptual apparatus offer some useful insights. Relevant key findings are as follows: (1) We do not encode information perfectly; (2) Our attention is spotlight-like—we stitch together broader images from the pieces that we focus on; (3) We are selective in what information we take in; and (4) We privilege certain kinds of information over others. We consider research in support of each of these key findings below.

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Less-than-Perfect Encoding. Our visual perceptual apparatus is designed such that we carry out less-than-perfect encoding of information. Minor movements of our eyes, microsaccades, are necessary so that we don't habituate on objects in our visual field. Microsaccades are involuntary and they basically "refresh the picture." If the image on our computer did not refresh, we would be left with an old image. This is not the case with our eyes. If we were to habituate on the visual stimuli, the image would simply fade away. Therefore, one could argue that our eyes are able to see because at times we cannot see (Martinez-Conde, Macknik, Troncoso, & Dyar, 2006). Microsaccades occur very quickly and prevent continuous perception, even if we don't realize that we do not continuously perceive information from the outside world (e.g. Martinez-Conde, Macknik, & Hubel, 2004; Morrone & Burr, 2006).

Each time we shift our attention from one thing to another, we engage in another form of movement and resulting visual suppression called a saccade. Saccades are quick, simultaneous movements of both eyes in the same direction. They last from about 20 to 200 ms (e.g., Ibbotson, Crowder, Cloherty, Price, & Mustari, 2008). The visual image is briefly suppressed to prevent blurring of the image. Saccades are considered voluntary compared to microsaccades because we can attempt to suppress saccades by holding our focus on one thing. The combination of microsaccades and saccades results in a kind of inherent "blink" in our visual system, even though we have the impression that we are seeing everything that comes our way.

Spotlight-like Attention. Further, our visual apparatus is designed to take in small, focused parts of a broader image in a manner often likened to the image that falls in the beam of a flashlight or spotlight. These small yet high-resolution images are stitched together to form the larger image. Rather than look at a scene in a steady way, the eyes move around, locating interesting parts of the scene and building up a mental "map" corresponding to the scene (Posner, Snyder, & Davidson, 1980). By moving the eye so that small parts of a scene can be sensed with greater resolution, bodily resources can be used more efficiently. (If an entire scene were viewed in high resolution, the diameter of the optic nerve would need to be larger than the diameter of the eyeball itself.) However, this kind of focusing apparatus comes with the cost of potentially missing the bigger picture. Images in the middle of the scene are most likely to be perceived. While still the prevailing model, the spotlight analogy for visual perception has been critiqued for being too simplistic (Cave & Bichot, 1999). Recent research elaborates on this claim. It reveals, for instance, that the characteristics of stimuli towards the edges impact perception (Müller & Ebeling, 2008) and there may be some variation according to individual preferences (Kastner & McMains, 2007) as well as individual differences (Heitz & Engle, 2007). There may also be differences in how certain populations, such as those with dyslexia, process visual stimuli (personal communication, T. Rose, 2008).

A body of research referred to as "change blindness" examines our inability to detect changes even when they are happening right before our eyes and even when we are aware that *something* is changing (e.g., Grimes, 1996; McConkie & Currie, 1996; Rensink, O'Regan, & Clark, 1997; Simons & Levin, 1998). Change blindness is a broad term and covers a range of phenomena at different levels, but at the most basic level, it appears to be a consequence of the combination of microsaccades, saccadic suppression, and this “stitching together of smaller, focused images.” In order to detect change, we need to map the scene as it was and we need to compare this to a mapping of the scene after the change. However, stitching together spotlight beams of images to create a bigger picture of a scene, and then doing that again in order to make a comparison, is taxing from a cognitive perspective.

Even when we know that something is changing, it can be hard to detect the precise nature or features of the change. “Blink” is built into our visual system due to microsaccades, saccades, and stitching together beams of focus to assemble a larger scene. However, most of the time, we aren’t aware that changes are taking place—we are incidentally encoding information and don’t attend to the details of a scene. This results in change blindness at a much broader level. A series of experiments by Simons and Levin (1998) referred to as “the rude door changer” illustrates this phenomenon. An experimenter approached a stranger on the street to ask directions. While the stranger was giving directions to the experimenter, two “rude” movers walked in between them carrying a large door, blocking the stranger’s view of the experimenter. Amidst the interruption, the experimenter was replaced by a second experimenter, in similar clothes, whose appearance was not dramatically different, though certainly not the same. Fifty percent of the strangers in this experiment thought they were talking to the same person before and after the “rude” movers walked through, completely missing the switch!

Selective Processing. Another body of research, on a phenomenon called inattentional blindness (IB), helps to illustrate that the source of attentional difficulties extends well beyond our visual system. Research shows that people often do not notice stimuli that are right in front of them if they are attending to something else (e.g., Mack & Rock, 1998; Most, Scholl, Clifford, & Simons, 2005). Haines (1991) gives the unnerving example of airline pilots during a simulated landing who are so focused on the control console that they miss the fact that the runway in front of them is blocked by another plane. Inattentional blindness can be so complete that after finishing their simulated landing, those test pilots said that they never realized that there was anything obstructing their way. Moreover, while much of the inattentional blindness research has focused on visual perception, there is evidence to suggest that without focused attention, other senses are also impacted. Mack and Rock (1998) have reported similar findings from their investigations into auditory stimulation (conducted with their colleague, Jack Hoppenstand) and into tactile stimulation.

How can we make sense of these events? Most of us tend to believe that we perceive something as a consequence of attending to it. However, as this research indicates, humans are selective about what information we take in and we prioritize some forms of information over others. We process only portions of the steady stream of stimulation headed our way because we can’t possibly take in everything going on around us. Indeed, research (e.g. Mack & Rock, 1998) suggests that perception and attention are distinct but related phenomena, and there are different levels of perception and attention. Perception can be both unconscious and conscious. Unconscious perception refers to the early processing of perceptual stimuli prior to awareness. Sensory stimulation is being processed, but we aren’t aware of it. Conscious perception, in contrast, refers to the processing of perceptual stimuli once attention is engaged.

Attention refers to our ability—intentional or unintentional, and with more or less depth—to turn our cognitive powers toward the stimuli we detect in the world. So it serves as a filter between all the stimuli in the world and our limited ability to be conscious of things around us. We direct our attention to more things than we consciously become aware of, but we cannot become aware of anything that doesn't capture our attention. As Lamme (2003) explains: "It seems that attention guards the gate towards a representation that can be consciously reported or remembered (as in IB). . . Many sensory inputs reach the brain and, via the process of attentive selection, some of these reach a conscious state, which allows us to report about them" (p. 12). A steady stream of information reaches us that we are not consciously aware of and, from the viewpoint of our attention, we simply miss. Yet other information makes it "through the gate."

Research also reveals the surprising reality that sometimes things in front of us do capture our attention—that is, our eyes might briefly move toward a new object in our visual field, for instance, toward the plane blocking the runway—but we never become *aware* that the object is there. Most and his colleagues (2005) summarize this puzzling interaction between implicit and explicit perception and the fundamental paradox that it creates: "On one hand, people engaging in challenging tasks must often maintain focus, effectively ignoring irrelevant information that might distract them from their goal. . . On the other hand, attention must be distractible; if potentially dangerous or behaviorally relevant objects appear, they should divert cognitive resources" (p. 218).

What does this research suggest for how the public takes in scientific information? It reveals that the information that we consciously attend to is more limited than we realize. What scientists, educators, and communicators assume the public takes in may be incongruous with the actual information people are able or inclined to attend to. Indeed, we humans prioritize attending to certain kinds of information over others even *before* becoming aware that we are taking in information at all. So what makes us more or less likely to notice certain information over other?

Influences on What We Take In. Experimental psychologists have conducted a range of studies to find out what makes us more or less likely to notice something that is right before our eyes. Attentional capture is impacted by a number of variables pertaining to stimuli, for instance, size, location, familiarity, loudness, the image or sound of our own names, and certain emotional stimuli including faces (e.g., Eastwood, Smilek, & Merikle, 2001; Moray, 1959; Ohman, Flykt, & Esteves, 2001; Vuilleumier, 2005; Yamasaki, LaBar, & McCarthy, 2002). Very large and very loud stimuli are likely to break through and demand our attention. There is also clear evidence that the meaningfulness and relevance of the stimulus impact whether or not we notice it. Meaningfulness even outweighs how recently we were exposed to a stimulus: we are less likely to notice a person whom we passed by yesterday than we are to notice someone whose face has meaning for us.

One of the keys to the door between attention and awareness is expectation. Expectation is so powerful that we often find patterns and representations (and assign them meaning) even when what we see is random (Shermer, 2009). There is some evidence that expecting to see a stimulus impacts how our brains respond to it. According to Treisman (2009), “Neural changes can specify the timing of attention effects. Functional MRI activation and single-unit changes occurring in anticipation of the stimulus have proved that attention can affect the baseline activity in specialized extrastriate areas even before the stimulus is presented” (p. 196, citing Chawla, Rees, & Friston, 1999; see also Hopfinger, Buonocore, & Mangun, 2000; Kastner & Ungerleider, 2000).

Further, the more demanding the task, the more expectation matters (White & Davies, 2008). This suggests that when we’re working hard to comprehend complex information, like scientific evidence and interpretations, expectation may have a pronounced effect on our ability to focus our attention on the myriad pieces of information before us. This tendency can be helpful and protective—for instance, we are neurologically and cognitively attuned to notice faces of people we recognize in the midst of teeming crowds (Buchen, 2008). However, it can also lead us to construe patterns that are not there.

Expectation is not always explicit. According to Gagnepain and colleagues, “Implicit memory has been defined as the expression of past experiences occurring beyond the boundaries of consciousness and without any intentional recollection” (Gagnepain, Lebreton, Desgranges, & Eustache, 2008, p. 276). They point to priming as one of the most well-known phenomena of implicit memory. Priming refers to “a change in the speed or accuracy with which a stimulus is processed, following prior experience of the same or related stimulus” (p. 276). Priming can occur through repeated exposure to a stimulus whether we are aware of it or not. For instance, if we pass a certain person on the street everyday, whether or not we attend to the person, we are more likely to select that person than another stranger as familiar.

Priming turns out to be a powerful psychological predictor of how we implicitly perceive and subsequently attend to stimuli. Having detected a stimulus once makes us more likely in the future to attend to it; this is a form of priming (Hinojosa, Pozo, Méndez-Bértolo, & Luna, 2009). Even our speech is unexpectedly primed—the way we form our sentences tends to mimic the syntactic structure of sentences we’ve just heard before crafting our own (Pickering & Branigan, 1999). Experiments have shown that we are primed by visual imagery too: for example, women smokers on a diet tended to associate smoking with weight control if, before being questioned, they viewed pictures of models rather than neutral photos of nature (McKee, Nhean, Hinson, & Mase, 2006). According to Mack and Rock (1998), “There is now ample evidence in the literature that sensitive, direct methods of testing often reveal that perceptions not consciously experienced seem to be encoded, and facilitate or inhibit subsequent perception when that same or a related stimulus object is subsequently presented to the observer” (p. 173).

Expectation not only shapes what we become aware of, but what meaning we make of that which we consciously consider and also how we behave. For example, researchers suggest that being primed with ideas of hostility can make us more likely to judge someone we don’t know as being hostile (Garcia, Weaver, Moskowitz,

& Darley, 2002). Negative terms tend to prime us for negative judgment, and positive to positive. Yet the expectations we develop through association can be quite specific—we distinguish guilt from sadness, for instance, suggesting that we're sensitive to the particular meaning of an idea and not simply its valence (Zemack-Rugar, Bettman, & Fitzsimmons, 2007).

Priming has also been shown to impact behavior. Unconscious cues that are related to meanings or beliefs we already hold can shape our subsequent action. For instance, people primed with words associated with the elderly (like "old" or "Florida") left a psychology study by walking more slowly than people who weren't primed that way (Berger, 2008, referencing Bargh, Chen, & Burrows, 1996). Researchers suggest that priming was at work when sales of the Mars candy bar rose unexpectedly and anomalously after the U.S. space program landed an exploratory craft on the red planet (Berger, 2008).

In light of this copious research on perception, attention, and awareness, what insights can we glean about how we present scientific information to the public? While there are many, we propose a few salient lessons. Perhaps most importantly, we should recognize that human attention is imperfect. Presentations that require constant focused attention to glean their meaning, such as those that follow a carefully crafted, linear narrative, may fail to connect. Yet this is the format of most scientific papers: researchers trace the logic of the research project through a parsimonious and lean account that minimizes repetition. This same logical structure, which demands "perfect attention," often governs class lectures and public presentations. Scholars may have developed coping strategies, for instance, by investing effort into monitoring their own attention and rereading passages of text. But we ask too much of the public if we require audiences to revisit scientific information multiple times in order to attend to it. Instead, we might mirror the design of successful educational television programs that account for attentional blink by revisiting the main storyline at multiple points and in varied ways.

The process of "stitching together images" given our "beam of focus" to glean the bigger picture has clear implications for the layout of published reports and the visual display of important messages. Attentional capture is unlikely to happen unless information in one of those initial "beams" breaks through. Images in the center of a scene are the most likely to be detected by the most people. In addition, we are more likely to shift our attention between different parts of one object than between different objects (e.g., Egly, Driver, & Rafal, 1994; Tipper & Behrmann, 1996). Finding ways in scientific presentations to bind together important images may help readers attend to multiple key points. We might also heed the finding that certain emotional stimuli—faces, guns, or our own names—have privileged access to human attention (Blanchette, 2006; Mack & Rock, 1998). Further, we have all felt the impact of an emotionally charged image that endures, that continually creeps back into our consciousness. Given their aspiration to objectivity, scientists may feel that it is manipulative to gain the public's attention by using such stimuli, but in the steady stream of stimuli, familiar and sentimental images do have the advantage of garnering public attention over other stimuli.

Finally, being open to new information is not as easy as we think. We can implicitly take in information that primes what we later notice, how we react to it, and how willing we are to take in subsequent information that does not seem to fit. This suggests the importance of priming readers or viewers for salient points in a presentation. Research by Teige-Mocigemba and Klauer (2008) suggests that it may be possible to control priming and to strategically contradict its effects, for example, by intentionally thinking of something positive in negative priming instances and negative in positive priming instances. So, for instance, if an audience is likely to bring a set of implicit assumptions to their interpretation of scientific research, one might prime them at the outset with examples designed to contradict these assumptions.

Patterns of Engagement with Causal Complexity, Salience, and Risk

Even in cases where we gain the public's attention, how can we sustain this attention and encourage the public to view scientific findings as salient and, when prudent, to be willing to change their behaviors and opinions based on those findings? Research on how people attend to risk in situations that involve causal complexity introduces further challenges in sustaining public attention and impacting people's choices and behavior.

Risk perception is a broad-ranging and complex topic that can be studied from a number of academic angles, including the fields of psychology, sociology, cultural theory, cognitive psychology, decision theory, economics, medicine, and public health. Research on causal complexity analyzes the biases and mental shortcuts, or heuristics, that people tend to use when considering phenomena or explanations that have complicating features such as non-linearity, distributed causality, or time delays and spatial gaps (e.g., Feltovich, Spiro, & Coulson, 1993; Grotzer, 2003, 2004; Perkins & Grotzer, 2005; Wilensky & Resnick, 1999). Together, these bodies of scholarship suggest some interesting patterns in how people attach salience to research findings.

Often making sense of research findings involves the analysis of risk. Consider the factors at play when one decides whether it is safe to eat eggs during a salmonella outbreak, when one weighs the pros and cons of undergoing a new medical treatment, or when one evaluates legislation prompted by warnings about climate change. A person's analysis of risk perception and behavior is not entirely rational—it entails complex interactions between affect, cognition, and behavior that can result in seemingly puzzling behavior choices (Sunstein, 2002). For instance, people's actions suggest that the calculated, mathematical level of risk often differs from a person's perception of risk, and people are often unwilling to modify their behavior in instances where mathematics suggest that they should, and willing when the mathematics suggests otherwise (e.g., Slovic, Fischhoff, & Lichtenstein, 1982a, 1982b). For instance, Sunstein (2002) explains that, amidst the sniper attacks in the Metropolitan Washington D.C. area in the fall of 2002, people made significant changes in their behaviors, yet they did not make changes in dietary or driving habits that were, probabilistically, much more likely to cause them harm. Kahneman, Slovic, and Tversky (1982) and colleagues have carried out extensive research to demonstrate the difficulties people have in reasoning about probability (see also Slovic, Monahan, & MacGregor, 2000) as well as how people misjudge samples, make errors of prediction, and confuse correlation with causality, to name a few common difficulties.

Analyzing these difficulties reveals heuristics that people tend to engage in and how these can lead to certain risk assessments. These mental shortcuts have been extensively studied (e.g., Kahneman et al., 1982; Slovic, 2000; Tversky & Kahneman, 1973) and have been written about widely by scholars who study risk and the public's reaction to it (Gardner, 2008; Gilovich, 1991; Sunstein, 2002; Thaler & Sunstein, 2008). What are some of these heuristics and biases and how might they influence human behavior? We review some of the most well-known heuristics below and refer the interested reader to the many sources that explain these heuristics in detail (e.g. Kahneman et al., 1982; Sunstein, 2002).

The *availability heuristic* (Tversky & Kahneman, 1973) refers to people's tendency to make predictions based on the information that is most available to them, rather than on more systematic assessments. According to Slovic, Fischhoff and Lichtenstein (2000), it is defined as "judging the probability or frequency of an event by the ease with which relevant instances are imagined or by the number of such instances that are readily retrieved from memory" (p. 37). It is often the case that something we can recall easily also seems to us to occur frequently. For example, we might think that crime is a common occurrence in our hometown if crimes are frequently reported on the local news, or if a neighbor was a victim of crime. We tend to turn to narratives about events that have happened to us or to those around us rather than rely on statistical data.

The tendency to rely on affect as a shortcut (Slovic, 2000) is another common response pattern. *Affect heuristic* refers to the tendency to use emotion as a mental shortcut in judging risks and benefits (Slovic, 2000; Finucane, Alhakami, Slovic, & Johnson, 2000). So, for instance, if a person adores skydiving and loathes scuba diving, that person may underestimate the risk associated with jumping from planes and overestimate the risk of underwater exploration. Likewise, we tend to overestimate the benefits of activities we like. Another mental shortcut, *the proportionality effect*, refers to our tendency to place greater importance on reducing the proportion of a risk than the raw number of those affected by risk (Tversky & Kahneman, 1982). For example, as Cass Sunstein (2002) explains, people more often favor a hypothetical governmental intervention that would save one in 100 people out of a population of 1000 (10 lives) over an alternative intervention that would save one in a million out of a population of 200 million (200 lives). Though sometimes people consider proportions as well as raw numbers in assessing risk, and though factors such as morals, values, and affect are also at play, we generally prefer the greater proportional impact over the greater numerical one.

Such mental shortcuts have benefits when we have little information available to us or if we have to make a quick decision based upon whatever information we have.

Yet, they can be costly in those instances when we are tasked with reasoning about research data or other information of significant complexity. Drawing conclusions based on our prior personal experience tends to cause errors because we are basing those conclusions on a biased sample. For instance, dramatic images or events with shock value—like the example of crime above—that we can easily recall can lead us to overestimate the likelihood of certain kinds of events (Morgan et al., 1985). It can also lead us to focus less on everyday, mundane risks that are statistically more prevalent (Slovic, 2000). To continue the above example, when choosing an apartment and considering how safe a certain neighborhood is, we might scan our memory for cases of anything bad that happened there. If we can't think of any, we might conclude without any systematic data that the neighborhood must be safe. However, one dramatic crime event, even if it is a rare occurrence, might shift our entire sense of the neighborhood. At the same time, our attention to crime rates might cause us to miss or overlook information about higher cancer rates that might otherwise affect our view of the safety of that neighborhood.

As Sunstein (2002) has argued, it is likely that the key role of emotion in facilitating these heuristics is a consequence of the way our brains and bodies process information. LeDoux (1996, 2000, 2007) differentiates between emotional memories (implicit or unconscious memories), in which sensory information takes a direct path to and is processed in the amygdala, and memories of emotion (emplicit or conscious memories), which are processed at the level of the hippocampus and neocortex. Emotional memories help prompt our immediate reactions to a situation. Processing at the level of the hippocampus comes into play after this initial reaction, but at this point the body has already begun to respond to the emotional memory and we may already feel the impact of that first response, such as the feeling of a rush of adrenaline. LeDoux's research suggests that while the amygdala influences the information processing in the hippocampus and neocortex, the hippocampus and neocortex appear to have very little effect on the amygdala. This makes it difficult to consciously override what our bodies tell us or to change our unconscious responses in the future.

This distinction between levels of emotional response has important consequences for understanding how people normally reason. We tend to think that reasoning should be cool, rational, and emotionless. One might assume that our immediate responses are always problematic and that we need our secondary, reasoned response to prevail. But neuroscience research suggests that this separation is not necessarily possible except for people with certain brain impairments who reason passionlessly (Damasio, 1994). Further, it's not clear that such rationality is preferable: those with dispassion-producing brain impairments tend to be ill-equipped for real-world reasoning. The distinction itself may not be meaningful in people without impairments. According to Damasio, "Nature appears to have built the apparatus of rationality not just on top of the apparatus of biological regulation, but also *from* it and *with* it" (p. 128). Rather than view mind and body as separate—what Damasio calls "Descartes' error"—we should view our bodily reactions as part of a system prepared to respond to environmental dangers. However, as we consider below, it is possible that our immediate emotional responses may not always serve us well in a complex causal world.

Our emotions interact with how we handle the complex causality inherent in most risk situations. Our emotional responses can lead us to reactions that help us to face certain kinds of causal features but to ignore others. Immediate and innate fear reactions, which evolutionary biologists postulate may persist in humans because they helped protect our ancestors from danger, are generated in the amygdala and bypass the reasoning region of the neocortex (LeDoux, n.d.). For instance, if you are eating lunch and a wasp descends upon you, you are likely to spring into action to escape assault. For most people, wasp stings are not life threatening, but one can readily connect the wasp (cause) with the stings it can inflict (effect) through a simple and spatially proximate chain of causal reasoning. The amygdala mobilizes action and one does not have to engage higher order reasoning to respond. However, you might be willing to sit next to a colleague who is smoking cigarettes and not give it a second thought. Your colleague's cigarette is unlikely to trigger an immediate emotional response and/or concern about the risk posed by it because, in contrast to the wasp, thinking about the risk of cigarette smoke requires grappling with temporally distant causes and effects, non-obvious causes, and compounded probabilities.

When reasoning about complex phenomena, people tend to make assumptions about the nature of the causality involved. These assumptions are often at odds with the forms of causality inherent in those phenomena. Feltovich et al. (1993) identified characteristics of concepts or situations that cause difficulty for most people and found that people tend to simplify phenomena, exercising a reductive bias. The authors explain that people often reduce dynamic phenomena to static "snapshots" and continuous processes into discrete steps. For example, one might inappropriately interpret the weather on a given day as evidence for or against climate change without reasoning about longer term changes over time. Subsequent research found that people rely on an array of similar tendencies in situations involving complex causality (e.g., Grotzer, 2004; Perkins & Grotzer, 2005; Resnick, 1996). According to Grotzer (2009), people in these situations typically assume the following:

> 1) linearity as opposed to nonlinearity in the relation of cause(s) and effect; 2) direct connections between causes and effects without intervening steps or indirect connections; 3) unidirectionality as opposed to bidirectionality*;* 4) sequentiality as opposed to simultaneity; 5) obvious and perceptible as opposed to non-obvious and imperceptible causes and effects; 6) active or intentional agents as opposed to non-intentional ones; 7) determinism—wherein effects must consistently follow "causes" or the "cause" is not considered to be the cause—as opposed to probabilistic causation; 8) spatial and temporal contiguity between causes and effects as opposed to spatial gaps or temporal delays; and 9) centralized causes with few agents—missing more complex interactions or emergent effects—as opposed to decentralized causes or distributed agency. (pp. 57–58)

There is substantial support for these tendencies in the research literature (e.g., Chi, 2000; Feltovich et al., 1993; Ferrari & Chi, 1998; Grotzer, 2000; Grotzer & Basca, 2003; Hmelo-Silver, Pfeffer, & Malhotra, 2003; Houghton, Record, Bell, & Grotzer, 2000; Perkins & Grotzer, 2005; Wilensky & Resnick, 1999).

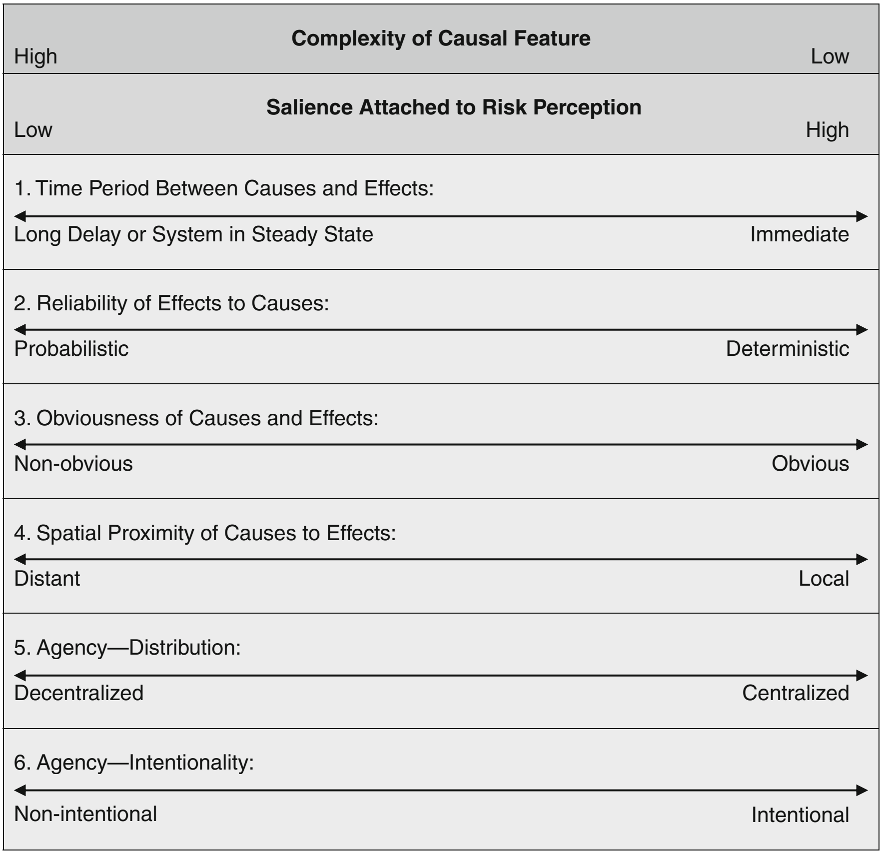

Fig. 2.1 Complex causal dimensions and perceptions of risk

The inherent causal complexity and the particular features of this complexity can interact with how we attend to and attach salience to particular risk situations and to related scientific information (Grotzer & Lincoln, 2007). Figure 2.1 illustrates the relationship between causal features and our tendency to attend to and attach salience to risk. Factors on the left side of the table are less likely to garner our perceptual, attentional, and cognitive resources than those on the right. By failing to process these left-side features, which tend to characterize causally complex situations, we may misconstrue the nature of a given phenomenon and thus ignore certain forms of risk. For example, people have difficulty reasoning about time delays. Time delays are a feature of a number of causally complex phenomena (recall the potential risk associated with sitting near your cigarette-smoking colleague). Since we have difficulty reasoning about time delays, we struggle to perceive causal relationships that are temporally distant; ultimately, we are less likely to perceive a particular time-delayed cause as related to later risk.

While one can roughly think about each of the features in Fig. 2.1 as existing along a continuum, there is more nuance to each than is set out in the diagram. For instance, complex causality along the temporal dimension can take a number of forms: delay between cause and effect, slow accumulation of effects such that the effects are increasingly perceptible, trigger effects, immediate effects, and so on. It is also the case that these dimensions interact with one another. Slowly accumulating effects may be initially non-obvious and become increasingly perceptible as the effects aggregate.

Particular risks can be assessed according to these dimensions. The development of AIDS (Acquired Immune Deficiency Syndrome) is characterized by a long latency period and extreme uncertainty from the point of HIV exposure to the onset of disease (Becker & Joseph, 1988; Prohanska, Albrecht, Levy, Sugrue, & Kim, 1990). It involves a non-obvious causal mechanism, temporal delays between causes and effects, and patterns of spread that involve decentralized causality. Assessing risk of contracting AIDS involves probabilistic causation about various risk-related behaviors and, indeed, about the behavior of the underlying mechanism itself (since HIV, as we currently understand it, does not lead to disease in all infected individuals). Causal features such as these are much harder to hold salient than those that trigger our innate fear mechanisms, such as immediacy, intentionality, and obvious causes and outcomes. The lack of these fear-triggering features means that we also find it difficult to attend to the research on global warming, which involves many forms of complexity: the effect is cumulative, there is a larger temporal and spatial gap between the cause and the effect, and the causes are distributed and non-intentional, to name a few.

Research on how people handle particular risks offers support for this interpretation of how complex causality and risk interact. For instance, people are more likely to go off of their statin heart medicine than their arthritis medicine because of the difference in the immediacy of the effects (Jackson, 2000; Pepine, 2003). The result of stopping arthritis medication is immediate pain, whereas the result of stopping statin medication is a higher risk of heart problems in the long term, but not necessarily any immediate effects.

The situation in Picher, Oklahoma, vividly illustrates the interrelationship between these dimensions. For approximately 100 years, Picher was a prosperous mining town where many kinds of metals were extracted, mostly zinc and lead, but also cadmium and other metals (Keheley, 2006). The leftover material from the mining process, called "chat," was left in mountain-sized piles all around the town. Generations of children from Picher played on the chat piles and even had their birthday parties on them. In the early 1970s, the mining operations shut down, but the piles continued to loom over the town's playing fields and schoolyard.

In 1980, Picher was designated part of one of the largest Superfund sites in the United States (Tar Creek). The legacy of the mining that occurred in previous years became the subject of intense study and concern. Research from the 1980s and 1990s on the health of those living in or near the Superfund Site found elevated rates of stroke, kidney disease, high blood pressure, heart disease, skin cancer, and anemia (Neuberger, Mulhall, Pomatto, Sheverbush, & Hassanein, 1990). In the mid-1990s, 31% of children living in the 5 towns within the Superfund site were estimated to have lead poisoning, while 45% of children living in the most contaminated towns of Picher and neighboring Cardin were estimated to have lead poisoning (Osborn, 2006). These levels were much higher than the average rate of about 2% for both the state of Oklahoma and the entire United States (Agency for Toxic Substances and Disease Registry, 2004)—although they have declined in recent years, a likely result of remediation and education efforts. According to local educators, children in Picher experienced learning difficulties at a much higher rate than children in other towns of similar socio-economic status.

Yet families were reluctant to leave. After all, Picher was their home, the center of their lives and a source of great hometown pride. Many of the adults had lived in Picher for years, had themselves played on the chat piles as children, and had grown accustomed to the many scientists taking samples from their homes and yards. One of the authors of this chapter, Rebecca Lincoln, was also one of the researchers working in Picher. Some of her work involved collecting samples of dust, air, and water in people's homes to test for lead and other metals, but she found that, among the people whose homes she studied, opinions on whether the chat was a risk or not varied greatly. Many people to whom she talked felt that because they had grown up in Picher and had turned out fine, it was probably safe for their kids, too.

In terms of complex causal features, the cause of the problem in Picher was non-obvious. While one could see the chat piles, the dangers that they posed were invisible. Quotes from a documentary entitled, "The Creek Runs Red" illustrate the townspeople's reactions (Beesley, Brannum, & Payne, 2006). As one teenager from Picher framed it, "I like Picher, Picher wouldn't be Picher without the chat piles." People couldn't see lead in the air or in the soil around their playgrounds and yards. It wasn't until the effects became visible that people could more easily attend to what was in the chat. As one town resident put it, "When the red water started to flow into the creek, that's when the trouble started." Further, the effects on the children were slow and accumulative. Staying one more day wasn't likely to result in a noticeable difference in one's health outcomes. Indeed, slowly developing effects are perhaps the hardest to detect and respond to—they require sustained effort and attention. Those effects also had a probabilistic aspect since not everyone was visibly affected or sick. When a home buy-out plan was offered to families with children under 6 years old, some but not all moved away. As one town resident expressed, "It's still a good town, and there's nothing wrong with it. There's absolutely nothing wrong with it."

The tendency to ignore non-obvious, slowly accumulating causes is perhaps most powerful in a case like this, where risks are pitted against a strongly ingrained way of life and a deeply held, emotion-laden conception of home. As one resident put it, "I'm the fourth generation to live here and my kids are the fifth, and that means something" (Beesley, Brannum, & Payne, 2006). Further, the economic challenges of leaving were acute because most families had all of their resources invested in their homes. However, even smaller changes in behavior were hard to achieve. One mother talked about coming back to Picher following her divorce so that she would have the support of her family. During the videotaped interview, she watches as her preschool child rolls down the chat pile to play. It makes the viewer wonder how differently she might have responded if she spotted a piece of glass in the chat or if a wasp landed on her child.

In 2006, a new problem came to light in Picher when results of a subsidence study were made public (U.S. Army Corps of Engineers, 2006). While the original mining was conducted such that support structures were left in place to prevent cave-ins, later "rogue mining" had resulted in the removal of many of these structures and studies showed that town structures were now vulnerable to caving in. In fact, a number of cave-ins related to the abandoned mines had occurred over the years, some of them within the Picher city limits and encompassing roads and houses (Luza, 1986). Whereas lead accumulation had non-obvious effects, the large sink holes that threatened to swallow Picher homes were startlingly obvious and dramatic, and the 2006 report brought this problem to the forefront of area residents' minds. The comments of Senator Jim Inhofe, who represented the area, made clear the differential impact of the two kinds of effects when he said, "an elementary school could fall in and kids could be killed. That's much more of a threat than some lead would be to someone's health" (Myers & Gillham, 2006). Plans were made to move all residents from Picher; however, some were still unwilling to go. The possibility of structures falling into sink holes entails probabilistic causality, since some homes fall and others do not. However, if one looks at the problem another way, the question of whether or not one managed to leave town before losing a house to a sink hole was a simple either/or proposition. Unlike the impacts of a slowly accumulating toxin, if people managed to escape before their homes fell in, they would suffer no ill effects. The obvious and dramatic effects compelled action when the non-obvious, accumulative ones did not. In reality, it is possible that the additional risk posed by the sink holes simply tipped the already tilting balance, though that was not how many, including the senator, framed the situation.

On May 10, 2008, Picher was dealt another blow, this one with causal features and effects that were impossible to ignore. Picher was struck by one of the deadliest tornadoes in Oklahoma history. The city suffered extensive damage, with eight people killed and 150 injured (Kimball, Stogsdill, & Palmer, 2008). The government offered no funds for rebuilding, focusing instead on relocation. Picher started the process of moving people out, dissolving its various town structures, and closing its schools and post office. The town ceased its existence as a municipality in September of 2009.

The events in Picher help illustrate how obvious, immediate causes with discernible effects garner our attention and precipitate action. What are the implications of these tendencies for communicating the results and implications of scientific research? Analyzing the inherent causal features in a given body of research results is an important first step in figuring out why some research does not garner the attention that scientists believe it warrants, and how to help make abstract and complex phenomena more understandable. Scientists may also need to find ways to make non-obvious causes obvious to the public, for instance, by showing simulated time lapse videos to suggest the outcomes of slowly accumulating causes, or by representing causes and effects that span large spatial scales in ways that fall within our attentional boundaries.

The Nature of Science

To this point, we have illustrated the challenges of gaining and sustaining public attention and in helping the public to reason about complexity. However, the difficulties that people have in grasping the results of scientific research are not solely attributable to the processes of human cognition. The nature of science—namely, what constitutes scientific knowledge and how such knowledge is generated—further complicates the enterprise. The unique epistemology of science is such that deep understanding of research results requires sustained attention—and we have seen what an elusive and complicated commodity that can be.

What is it about the nature of science that necessitates this sustained attention? It is the very processes by which scientists generate knowledge. For starters, there is no one way to "do" science. Methods and practices vary widely across fields, institutions, and individuals. Even the U.S. National Science Teachers Association (NSTA) asserts, contrary to decades-old school lore, that "no single universal step-by-step scientific method captures the complexity of doing science" (National Science Teachers Association, 2000). Amidst this array of approaches to doing science, there exists considerable debate amongst the general public and academics from a range of disciplines about how to characterize scientific inquiry. The lack of agreement about what constitutes "science," while intellectually exciting, can become particularly volatile in the public realm—as when people are trying to make decisions about everyday life such as how often mammograms should be given or whether intelligent design should be taught in schools.

What counts as "science," then, is not always straightforward. Nonetheless, many scholars who specialize in scientific epistemology agree that most scientific knowledge has some features in common (see Guisasola, Almudí, & Furió, 2005 for discussion and additional sources on the characteristics of scientific knowledge). The NSTA (2000) offers a rare succinct portrayal, highlighting "the systematic gathering of information through various forms of direct and indirect observations and the testing of this information by methods including, but not limited to, experimentation" and "…a demand for naturalistic explanations supported by empirical evidence that are, at least in principle, testable against the natural world." They also agree that scientific knowledge is necessarily *tentative*. Our understanding of the world is elaborated, refined, revised, and even replaced as new evidence and more promising theories emerge. Whether the process is one of evolution or revolution, scientists routinely seek to "trade up" their existing concepts for more fruitful and parsimonious models of phenomena (e.g., Bauer, 1992; Chalmers, 1999; Guisasola et al., 2005; Kuhn, 1962).

The generally agreed-upon models that prevail in a given field at a given time function as frameworks that structure scientific work. Whether called theories or paradigms, and whether considered influences on or determinants of scientific programs, these models shape the questions that it makes sense to ask, what kind of evidence to seek, what constitutes a "fact" or a reliable observation, and what a set of findings could mean (Bauer, 1992).

Although these features might read like a set of constraints, they enable scientists to produce a wealth of reliable and useful knowledge. But they can present challenges to public understanding. Consider the example of autism research. In the 1960s, the prevailing scientific theories attributed childhood autism to the influence of "Refrigerator Parents," particularly mothers (Bettelheim, 1967). Autism was considered to be the child's response to cold, unloving environments—a retreat from a harsh family life. The findings supporting these theories may have been artifacts of the population studied—typically upper-, middle-class families which tended to have more formal households than others did and that researchers judged as cold (whether substantiated or not) based upon their formality. Further, if autism has a genetic component, what the researchers interpreted as "coldness" may have been behaviors related to autism in parents. In the 1970s, the "Refrigerator Parent" theory was debunked and now researchers are focusing on the interaction of genetic and environmental factors in autism, though much uncertainty remains. One can only imagine the emotional toll those earlier theories took on parents who were told that their child's autism was a result of inadequate love.

Scholars' view that scientific knowledge progresses through revising or replacing models is different from the view most people hold. The public tends to think of science as an accumulation of facts (Bauer, 1992; Chalmers, 1999)—the "brick-like" building up or accumulation of knowledge. According to Bauer (1992), a fable about science is that it "is commonly taken to connote fact or certainty" (p. 63). Thus, when scientists amend their knowledge they might appear to the public as waffling, uncertain, or unreliable.

All of this is complicated by the fact that the scientific enterprise involves a great deal of uncertainty. If scientists fail to explain the meaning of uncertainty in scientific research, that uncertainty may undermine public acceptance of widely accepted scientific results (Zehr, 1999). According to Koslowski (1996), uncertainty pervades scientific work—for instance, scientists may temporarily ignore disconfirming data until they formulate a solid theory. They then return to those data to try to develop a unifying theory. They also may use "working hypotheses" that don't fit all available data to reduce information-processing demands and to enable patterns to emerge. Scientists may prefer a particular theory because it is the best theory for now and because rival theories are deficient. Any one of these aspects of scientific work makes it complicated to simply "bring the public along for the ride."

Given the patterns of uncertainty and certainty, vision and revision that are central to scientific pursuits, one can imagine frustrated members of the public doubting the value of scientific knowledge, or placing their confidence in other, more unvarying knowledge claimants. According to Bauer (1992), science tends to yield better predictions than folklore or mysticism, even though we cannot assert that it deals in "facts." Scientific knowledge, he explains, might be better conceived of as a map—not facts or reality itself. Instead, scientific knowledge is a representation that helps us understand and make predictions. This is quite a different conception from the brick-like accumulation of facts that many people envision.

This disjuncture between scientists' and the public's assumptions about the nature of science, combined with the challenges we have attending to complex scientific information, can lead to alarming instances of miscommunication. Peter Doran, a polar scientist at the University of Illinois at Chicago, wrote a 2002 article in *Nature* attempting to share the results of his findings pertaining to the hole in the ozone layer over Antarctica. Doran and colleagues (2002) wrote that between 1966 and 2000, 58% of Antarctica had cooled due to bans on ozone destroying chemicals, but that the rest of the continent was warming with the rest of the world. In subsequent press reports, Doran's findings were misinterpreted as evidence of overall cooling in Antarctica. It appeared to the public that Doran was offering evidence against climate change—that scientists were changing their minds. Instead, Doran was contributing a piece of evidence to a complex puzzle that, as a whole, agreed with climate change findings. Doran (2006) found himself in a protracted effort to clarify the points.

This particular example involves considerable cognitive complexity. Reasoning about two causes working in opposite directions with different local effects is quite demanding. Further, research shows that many people believe that climate change is caused by changes in the ozone (Sterman & Booth-Sweeney, 2002). Therefore, the public was likely to conflate the causes, not to put them in juxtaposition. To many, saying that the ban on ozone resulted in cooling was equivalent to saying that global warming was not actually happening. *Confirmation bias*, the tendency to selectively sample information that is consistent with a hypothesis and to ignore contradictory information (e.g., not searching for disconfirming evidence), is a well-studied and common phenomenon (e.g., Nickerson, Perkins, & Smith, 1985). Those looking for evidence against warming of the atmosphere jumped on one piece of Doran's evidence and excluded the rest, either intentionally or, quite possibly, because they missed the complexity in the argument. Despite numerous attempts to set the record straight, Doran found that his research continued to be misinterpreted in the public arena, and was even held up as an example of scientists' inconsistency rather than as part of a larger effort to develop a robust and reliable knowledge base.

Shapin (1992) has argued that science has become more isolated from the public than it was in early modern society. He offers the example that one could walk into a mill but cannot just walk into CERN, The European Organization for Nuclear Research. This, he argues, has contributed to fundamental problems of the place of science in society. He calls for the importance of finding ways to communicate the workings of science to the general public—not only what scientists know, but how they know and to what levels of certainty.

The challenges that we have discussed make it clear that there are many factors working against public understanding of science and that the public's response to scientific research is often highly reasonable considering what is being asked of them. It puts an incredible burden on scientists in terms of helping the public achieve understanding of scientific work. However, it is possible that the challenges will be less pronounced in the future because later generations may understand the processes of science to a greater extent than most of us do today. The science education community has called for helping students understand the epistemological commitments that scientists make—the "processes scientists value for generating and validating knowledge" (Sandoval & Reiser, 2004, p. 345). The U.S. national science standards ask educators to help students understand the epistemology of science, particularly the ways of knowing and finding out in the discipline. The standards emphasize the role of theories, evidence, uncertainty, and change in how scientists conduct their work, noting that "scientists develop explanations using observations (evidence) and what they already know about the world (scientific knowledge). Good explanations are based on evidence from investigations" (National Research Council, 1995). The standards also emphasize the importance of "trading up" for more powerful models, asserting that "scientific explanations emphasize evidence, have logically consistent arguments, and use scientific principles, models, and theories. The scientific community accepts and uses such explanations until displaced by better scientific ones. When such displacement occurs, science advances" (NRC, 1995).

Research shows that students can learn to think about epistemological issues (Smith, Maclin, Houghton, & Hennessey, 2000) and that explicit discussion of epistemology encourages more informed views of the nature of science (Khishfe & Abd-El-Khalick, 2002). Research also reveals the value of infusing learning about the nature of science in science education. One line of study suggests that a limiting factor in how people reason about evidence is related to their epistemological development (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; Sandoval, 2003, 2005) and that those with greater epistemological knowledge perform better in science (e.g., Linn & Songer, 1993). This type of knowledge puts students in a better position to interpret research findings and to take part in the dialogue within and around scientific communities. And, eventually, it will help people think about and debate scientific concepts and evidence in the public arena.

We believe that understanding the nature of science is as important for an informed public as it is for scientists. Further, in positioning their research results, scientists will need to adopt a reflective stance on the differences between how they view science as an enterprise and how the public views it. Given the patterns of perception, attention, and cognition that guide how humans take in and deal with information, and the extent to which these patterns complicate the processing of complex information, communicating scientific results well necessarily engages scientists in thinking like cognitive scientists, philosophers, and sociologists of science. Awareness of these human patterns, how they interact with understanding the nature of science, and what that means for presenting scientific information to the public are critical pieces to the puzzle of helping promote public understanding of science.

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Chapter 3
The Natures of Scientific Thinking: Creativity as the Handmaiden to Logic in the Development of Public and Personal Knowledge

Keith S. Taber

Introduction

In this chapter I am going to make an argument for giving more emphasis to the role of creative thought in science education. Part of my argument is that we currently underemphasise the creative aspect of science compared with the 'logical' aspects. I also argue that there is also insufficient attention to the creative aspects of teaching and learning science – and that this may contribute to some of the problems faced by teachers and learners.

I approach this theme from two starting points. One of these relates to the well-recognised limitations in student understanding of the nature of science (NOS). In particular I consider the centrality of models in learning science: models are ubiquitous in science teaching, but may commonly be understood by students to be intended as realistic representations of reality, when many of them have a very different (partial, provisional, limited) status as either scientific or teaching models. The other starting point is an example of a common way that students think about a key area of science – where they demonstrate ideas that are flawed, illogical, un-naturalistic; yet quite creative in their own way.

After briefly reviewing the focus of logical thought in the sciences, the chapter then turns to consider the role of creativity in the scientific process, and argues that this is as important as logic. The chapter concludes by considering the role of creativity in learning science.

An Authentic Nature of Science for Science Education

In recent years there has been an increasing focus on how NOS is reflected in science education, especially at school level (Clough & Olson, 2008). The debate about the aims of science education – science for all, or science for future scientists – has been

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developed through an increasing focus on 'scientific literacy' (Millar & Osborne, 1998), the understanding of the NOS that is appropriate for people to function effectively in modern technologically advanced societies, and in particular in democracies struggling to balance industrial development with environmental stewardship. School leavers should be ready to be critical readers, savvy consumers, and informed voters, who are able to evaluate scientific claims and arguments.

It has been argued that this focus on scientific literacy is detrimental to those wishing to specialize in science – as it excludes much traditional 'content' and practical work, and reduces the knowledge base available to students to appreciate the abstract nature of science (Perks, 2006). However, I would argue that a focus on the processes of science not only supports the aim of education for all, but can also be seen to be central to understanding science for those looking to take advanced courses. After all, it is less important to know that carbon has an atomic mass of 12, or that there was an 'explosion' of new species in the Cambrian, than to have some notion of how such claims come about and then come to be widely accepted in science. This is certainly not an argument that science education should exclude or downplay the products of science (theories, models, laws, etc.) but rather than there should be a balance of engagement with both products and processes. That is, it is better to be more selective about the scientific products presented in school science, but to teach about them in the context of an understanding of scientific processes.

It is worth quoting here one strong critic of the shift in science syllabi toward teaching for scientific literacy, David Perks. Perks argues that 'traditional' teaching approaches focused on learning facts are misrepresented, but rather support sophisticated learning processes,

> Mastery on the part of the pupil involves acquiring factual knowledge and building models to incorporate this knowledge. As children progress they begin to realise that the models they have been taught are insufficient and need to be replaced, to accommodate new facts they are meeting about the way nature behaves. As well as refining the models they use to describe nature, students gradually become conscious of what it means to build and try out new models themselves. All the time they need to be confronted with the need to test their ideas against experimental evidence. (Perks, 2006, p. 19)

This is an interesting claim, as I would totally agree with Perks that this is what we might hope for (Taber, 2010b). However, I am less sure that Perk's model would withstand much testing against the experimental evidence: at least in terms of most of the thousands of students I have come across in my own time working in and visiting schools and colleges. This is a good aspiration, but – as is illustrated below – it does not reflect how most students experience meeting the sequences of models presented in school science.

Teaching NOS to Support Learning of the Science

There is a range of arguments put forward for the focus on NOS in science education, in terms of what it is most important for students to learn to support them as future citizens. However, there is also a strong argument for teaching about NOS to support teaching about the products of science themselves (Taber, 2010b). There is a considerable literature showing both that students commonly struggle to understand many scientific concepts, and that they often develop their own alternative understandings at odds with the scientific models (Duit, 2009). Scientific ideas are often very abstract, if not even counter-intuitive. Learning something of the process by which scientists have gradually come to adopt the ideas they have (with a taste of the evidence, and the debates, and the false paths and cul-de-sacs) can help students appreciate that even the scientific greats that they learn about went through a process of struggle, usually including rejecting many initial ideas, before formulating the scientific principles that are now widely accepted. This gives a much better impression of NOS than the catalogue of outcomes met in many science curricula – the so-called rhetoric of conclusions (Niaz & Rodriguez, 2000).

A more historical approach can also help learners appreciate that some of their own 'wrong' ideas are actually very similar to those scientists had seriously considered and tested (Piaget & Garcia, 1989). As generating ideas to test, a creative act discussed below, is an essential step in the research process, students should be encouraged to award themselves merit for generating such ideas. This does not imply a relativistic notion of science education – along the lines that students' ideas are just as worthy as the science in the curriculum, even when they are clearly contrary to accepted scientific ideas – a potential perspective which has been rightly criticised (Matthews, 2002; Scerri, 2003). Rather, such ideas should be valued in their own terms – as starting points for scientific investigation, that support a key part of the research process.

A related point is the difficulty pupils have in appreciating the status of many scientific 'products': school children often demonstrate very limited understanding of the types of entities created in science (Driver, Leach, Millar, & Scott, 1996; Taber, 2006):

- They may associate science with facts, and see models as intended to be replicas;
- They may consider theories to be hypotheses that have been tested and shown to be true,
- Or alternatively they may consider theories as no more than ideas that have not yet been proven, but which become converted to laws once they have been proved true by experiments.

A key issue is that science teaching, like science, relies heavily on the use of various forms of model. *In science* these models are often used as thinking tools to help explore ideas, as much as representations of what research has found out. *In teaching*, models are used both to simplify complex science (Taber, 2000), and to find ways of making connections with what students are already familiar with. None of that is in itself problematic, but unfortunately the nature of the models presented in teaching is not always explicit to learners – so, students often tend to take them as realistic representations of proven accounts of the world. These notions are not only epistemologically simplistic: they can act as significant pedagogic impediments to effective learning (Taber, 2001b, 2005).

In my own work I have talked to students close to despair at how some science teachers seem to take great pleasure telling a new class that the ideas they worked hard to learn the previous year are not actually right, and that *this year* they will need to learn how things really are. Besides being a distorted view of how science is represented in curricula, such pronouncements can be completely disheartening to students who have put real effort into making sense of, and learning, the ideas they were taught in school science.

The Problem of Teaching Without Making Modelling Explicit

Even when teachers do not act in such a careless way, our teaching may make a difficult and challenging subject more problematic for pupils than is necessary. I illustrate this with an example from the physical sciences, from the area of representing matter at the submicroscopic level.

When lower secondary students are introduced to the particle model for the three states of matter (e.g. at around 11 years of age), that model is usually presented as if the particles are non-interpenetrating spheres that are close-packed in solids (like tiny billiard balls, to use a common teaching analogy). These properties help explain the properties of the solid state (e.g. being rigid and hard to compress). In a liquid these particles are able to move past each other (so it can flow), and in a gas they are well separated in space (so it can be readily compressed).

And yet, when these same pupils are taught about thermal expansion, perhaps a year or two later, *this* phenomenon is explained in terms of a particle model where there is considerable space between the particles in a solid – and they are told that heating increases the spacing further. The solid retains its fixed shape, rigidity and hardness – but the model has changed, dropping the features which explained those properties.

Moreover, students are likely to be told that during thermal expansion the particle size does not change, but the space between those particles increases. They may even have it pointed out that if they get this wrong, and suggest in a test or examination that the particles themselves get bigger (as students commonly do), this will be marked wrong.

Thermal expansion leads to fewer particles per unit volume, so the average volume per particle increases. On the close-packed particle model (that students have been taught, and – not appreciating the nature of models – have largely accepted as the way the world is) this would imply that during thermal expansion each particle has greater volume (i.e. gets bigger), but this is considered ‘wrong’ according to school science, as *in this context* that is the wrong model to apply. This must seem nonsense to many young people attempting to make sense of the particle model of matter. It certainly seems nonsense to me.

Often the explanation for why the particles move further apart (to occupy a greater average volume, without getting any bigger!) is that heating provides energy that allows the solid particles to vibrate more. This is a fair reflection of the scientific model, but does not logically lead to any measurable expansion: if all the particles were to vibrate in phase, then greater magnitude of vibration would not require the particles to move further apart.

If these students later select to study science in advanced courses, they will find that they are given a new reason why greater vibration leads to expansion: this is explained in terms of the asymmetrical nature of the force-separation curve between particles. In other words, we teach secondary students an explanation that does not logically do the job, and only years later do we offer (a minority of students: those who have managed not to get put off the subject or confused by our apparently inconsistent and irrational explanations) a more sophisticated model that does a better job of explaining the phenomena.

I have never known a student to query the 'greater vibration' explanation. Perhaps this is because it fits intuitions, or because it is accompanied by convincing teaching models ('imagine it was very hot in here, and the class was all squashed together in one corner of the room: wouldn't you all try and move a bit further apart?') I suspect also that this is largely because the molecular world is such a mystery that most students are in no position to question what we teach them (Taber, 2001a).

There is more to this story. When students learn about the periodic table and atomic structure, the ball-like particles which they were introduced to some years before, and which they are now getting comfortable with, suddenly develop a complex structure. Those particles that were non-interpenetrating so that solids remained rigid, now turn out to mainly be empty space and comprised of atoms, which are themselves made of subatomic particles. Pupils generally just accept that the electrons occur in shells, and that the first shell fills up with two electrons, but the second eight. Many books at this level incorrectly imply that the third and subsequent shells also fill at eight electrons – but again students seldom ask why there is not room for more electrons in the larger shells. Perhaps one of the most telling points is that students seldom even question why the negatively charged electrons in these molecules and atoms seem to be able to link up in pairs (as in common representations in chemistry). They largely accept the model – presumably because they have learnt that science lessons are about receiving the 'facts' that scientists have discovered about the how the world is, as communicated through the authority of the teacher and the textbook.

When they study chemical reactions, these learners find that the particles that behaved like solids balls at the start of their secondary schooling, will now in certain situations interact with each other – often in quite telling ways (reflected on the macroscopic scale with colour changes, bangs, flashes, smells, etc). These interactions are not the elastic collisions of earlier grade levels, but involve the splitting, joining and exchanging of components, often associated with considerable releases of energy.

When chemical reactions are studied in secondary level, a lot of this is not well explained: and teachers commonly use the language of electrons being 'shared' between atoms and 'donated' and 'accepted' during transfers, or forming 'seas' in metals. This creative language is metaphorical, but where the teacher assumes it is obvious the metal lattice has to be neutral overall, students may imagine a vast excess of electrons acting as a sea around the cations (Taber, 2003). Students may have genuine difficulties in appreciating how anthropomorphic descriptions of the lives of atoms can apply figuratively in a factual subject such as science (Taber & Watts, 1996/2005).

Very commonly, in the 'explanatory vacuum' of secondary science, students come to develop an understanding of chemical phenomena in terms of atoms wanting to obtain full shells, or needing to get octets of electrons (Taber, 1998). They will often even explain a reaction as occurring *because of* the need for atoms to fill shells – even when given a chemical equation for the reaction which clearly shows all the reactants already meet that criterion (Taber, 2002b) – hardly an example of scientific thinking (see the example below – Fig. 3.1).

Why do hydrogen and fluorine react?

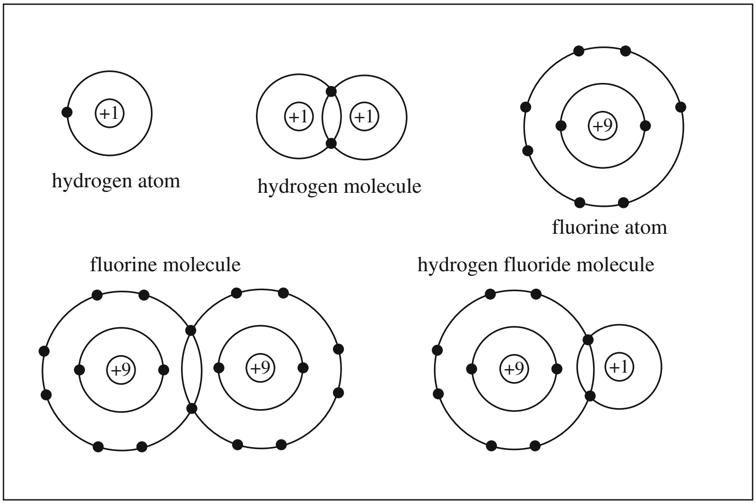
Hydrogen reacts with fluorine to give hydrogen fluoride. The equation for this reaction is:

$$\mathbf{H_{2(g)} + F_{2(g)} \rightarrow 2HF_{(g)}}$$

The word equation is:

hydrogen + fluorine → hydrogen fluoride

Look at the following diagrams:



In your own words, explain why you think hydrogen reacts with fluorine:

Fig. 3.1 A question about reactivity

Yet of course, if they take their study of chemistry to a more advanced level, they then find that the notion of shells is largely supplanted by a very different description that instead has orbitals describing electron probability densities. At this point I have found some students get very frustrated at being offered (and asked to learn) such apparently contradictory accounts. Yet much of the frustration comes from not having the nature of the models discussed made explicit throughout the stages of learning school science.

All of the models these students are asked to consider have their uses, even if they may seem inconsistent. Such inconsistency is hardly a desirable feature for teachers: but it is not the problem it may seem to students who think they are being provided with scientists' realist accounts of how the world actually is. Models of the atom as fuzzy fields of force may be much more sophisticated than the introductory model of close-packed spheres: but that latter model still has its uses. Scientists have no problems understanding what is mean by the labelling of the structures of many metallic crystals as 'close packed' – with cubic or hexagonal close packing – *for which purposes* those touching and non-interpenetrating spheres do a perfectly adequate modelling job.

The problem here is that learning *about models* is not authentic science education unless the teaching and learning is *explicitly about* models. Science education aims to help young people think scientifically, not just know some scientific facts. As Perks (2006) acknowledges in his critique of teaching for scientific literacy, *thinking through constructing and exploring models is a key part of scientific thinking*.

The Problem of Student Learning in Science

Given that much science teaching does not make the NOS, and the modes of scientific thought which are associated with it, explicit to learners, it may unsurprising that students do not always demonstrate the desired modes of scientific thinking that teachers wish to encourage. There is a vast literature on aspects of student thinking in science, and often it is found that students' ideas are rather at odds with the target knowledge which is set out in the curriculum (Duit, 2009; Taber, 2009b). Here I focus on one example that links with the previous section, but similar arguments could be made about many areas of students' learning in the sciences.

Consider the following question (see Fig. 3.1) and responses.

This question was part of a set of probes developed for teachers to use during a project funded by the UK's Royal Society of Chemistry (Taber, 2002a). The reader might just wish to pause and consider what they would consider an acceptable level of response from students who had done well in school science and were studying chemistry in post-compulsory college ('sixth form') courses.

It was found that when students were set this question, they produced a wide range of answers. However, even among advanced students (studying chemistry at University entrance level in post-compulsory education), a good many of the responses were along the lines of the following examples (Taber, 2002b):

> Fluorine is a halogen and has 7 outer electrons. To be stable it would like 8 electrons in its outer shell. By covalently bonding with the hydrogen atom which would like 2 electrons in its outer shell they form hydrogen fluoride which is stable
>
> Hydrogen has 1 valence electron in its outer shell, whereas, Fluorine has 7 outer electrons. As a full outer shell of electrons is wanted by both particles, the H atom will donate an electron to the Fl atom forming a paired bond completing both particles outer shell number
>
> Fluorine atoms have 1 'gap' where an electron is 'missing'. This means that in its valency shell, it only has 7 electrons. Hydrogen atoms have 1 'gap' where an electron is 'missing', though it is only meant to have 2 in its valence shell. Therefore the two atoms react to form full shells, the fluorine with 8 electrons, the hydrogen with 2 electrons.

Illogical Thinking

These, and many other responses, shared the following properties:

- they described the driving force of chemical reactions to be related to the attainment of stable electronic configurations (octets of electrons, full outer shells);
- the explanations were often focussed on what the individual atoms 'wanted', 'needed', and did.

Yet, the question referred to hydrogen and fluorine, both substances that exist as diatomic gases. In case students did not know or realise this, the question gave the formulae equation which specified the reactants as $H_{2(g)}$ and $F_{2(g)}$ (see Fig. 3.2).

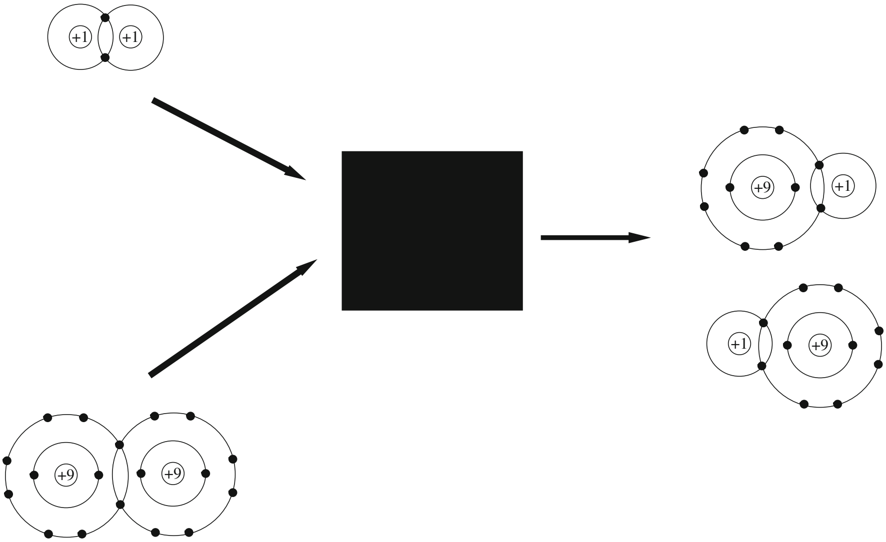


Fig. 3.2 A schematic representation of the reaction

Given the information in the question, the responses presented here are illogical. It is irrational to explain the interactions of hydrogen molecules and fluorine molecules in terms of the properties of different species entirely – the atoms (which are far too unstable to exist in any significant concentrations under normal conditions).

The ideas that are presented here by students may be labelled as 'misconceptions' or 'alternative conceptions', and indeed have been claimed to be part of a common way of thinking about chemistry among students at this level (Taber, 1998). Whilst it seems very likely that student thinking in chemistry is strongly influenced by 'intuitive' notions of the world (Taber & García Franco, 2010), it also seems clear that explanations of chemical phenomena in terms of the properties and 'behaviour' of atoms and molecules develop as a result of science teaching (rather than being intuitive theories of the world, or the kind of folk theories of the world which are often believed among lay people). After all, atoms are not objects of direct experience; and nor are they the subject of choice for social conversation among most adolescents.

Scientific Thinking

We are entitled to be concerned about such matters if part of the aim of science education is to teach scientific thinking – when we find the *outcome* of science education is often thinking about scientific concepts in such 'unscientific ways'. In the example discussed above we find illogical responses (in that the explanations are not consistent with the premises of the question) that rely on non-natural agency: the desires, needs, preferences of inanimate atoms. If we want to encourage scientific thinking, and we hope to develop logical and critical modes of thought, then something seems to be going very wrong.

Yet perhaps it would churlish to be too critical of the 'illogical' responses of students, given the nature of the teaching they commonly receive. If solids are hard and cannot readily be squeezed because they consist of close-packed spheres with no space between them, but they also expand on heating because the space between the spheres gets bigger, then why not explain the reaction of molecular materials in terms of the properties of atoms. If it seems science is flexible when it comes to explanations, then perhaps we can just select whatever premises best support a viable explanation.

Of course, the teacher may respond that using different (apparently contradictory) models of the submicroscopic structure of matter to explain different properties of solids is a scientifically acceptable procedure, whereas it is not scientifically acceptable to explain the behaviour of molecular substances in terms of discrete atoms. That might however seem an *ad hoc* response from the students' perspective: defending 'sleight of hand' (switching the model for one that does the job) by simply stating that it is a scientifically acceptable procedure does not seem to be in the spirit of science (as practice based on logical analysis of empirical evidence and critical thinking). It is no wonder so many students see science education as about receiving facts that are the outcome of some else's thinking – someone who has already been inducted into the great mysteries of the subject.

Logical Thinking

Despite these problems in science *education*, it is certainly the case that a key part of scientific thinking is being able to think logically. Science is based upon rational processes, so that knowledge claims are backed up by an argument chain (Toulmin, 1972). The following short extract from Sir Peter Medawar's speech accepting the 1960 Nobel Prize for Physiology of Medicine (for his work in immunology) gives a flavour of the kind of 'if-then' argumentation found in science:

> . . .if living cells from a mouse of strain CBA are injected into an adult mouse of strain A, the CBA cells will be destroyed by an immunological process, and the A-line mouse that received them will destroy any later graft of the same origin with the speed to be expected of an animal immunologically forearmed. But if the CBA cells are injected into a foetal or newborn A-line mouse, they are accepted; more than that, the A-line mouse, when it grows up, will accept any later graft from a CBA donor as if it were its own. (Medawar, 1960)

Often in school science students are expected to learn a heuristic for 'the scientific method', although modern philosophers of science have shown there is no such simple set of steps that describes a universal scientific method (Taber, 2009a). Scientific thought, although logical, is often more nuanced than the simple 'if this, then that' version of hypothesis testing found in some representations in school science.

The Logic of Scientific Discovery

Early approaches to exploring the scientific method were based on the trustworthiness of observation and measurement and on what might be considered a faith in human reasoning faculties. Simple logical considerations would suffice: e.g., if X occurs when Y is not present, then Y cannot be considered the cause of X. More difficult than excluding possibilities, was (and is) the question of what needs to be demonstrated to justify considering something as the cause for something else.

The problem of induction – proving general rules from testing any number of specific instances – hung like a cloud over science for many years. How can we prove that all samples of copper conduct electricity without actually testing all samples of copper? Again such complications tend to be underplayed in school science. A student asked to connect a piece of copper wire into a test circuit, and who observes the lamp glow, is expected *not* to conclude that this particular sample of copper conducts, but rather that copper, in general, conducts. Logically, this is another nonsense, of course, not because the procedure is inherently invalid as a learning activity (it can be a useful classroom demonstration for how we can test the conductivity of materials), but rather because the rich context that makes this a suitable practical activity to do in a school classroom is seldom clear to the students.

The great twentieth century philosopher of science, Sir Karl Popper, initially made his reputation in *the Logic of Scientific Discovery* (*Logik der Forschung*), where he demonstrated the intellectual courage to acknowledge that induction could never be justified in an absolute sense on logical grounds (Popper, 1934/1959). However, he did focus on the logical grounds for refuting ideas in science, and championed a demarcation criterion for scientific conjectures in terms of specifying the conditions under which an idea should be considered refuted. His 'hypothetical-deductive' model of how to test scientific ideas has been very influential, for example in notions of 'the scientific method' considered in school science. Of course others argued cogently that such logically clear procedures were in practice complicated in various ways, and scientists could sometimes have rational reasons to hold on to ideas that had failed some tests (Kuhn, 1996; Lakatos, 1970; Taber, 2009a).

Research design may often appear straightforward in the natural sciences where there are often well-established paradigms, but this only means that a whole host of assumptions are considered as the shared commitments of that particular research community (Kuhn, 1974/1977). Such strongly shared commitments within a research programme are less common outside of the natural sciences (Lakatos, 1970; Taber, 2009b), and are no assurance of infallibility in any disciplinary context.

Decision-Making in the Scientific Process

When graduate students prepare to become researchers in education, they are taught about the logic of the research process: that research questions should derive from a critical review of existing research; that it is important to be clear about the ontology of what is being investigated (what kind of thing are we dealing with here?), which allows careful consideration of epistemology (what kind of knowledge is it possible to have about this kind of thing?), and so informs viable methodology (Taber, 2007b). Their thesis is to be just that – a coherent and cogent argument – and there must be logical consistency throughout – so knowledge claims really do follow from an analysis which is appropriate for the kind of data collected; which is in turn suitable for answering the research questions; which themselves are informed by the ontological and epistemological analysis carried out to inform the methodology (e.g. see Fig. 3.3).

Of course, the process set out in Fig. 3.3 is quite complex. Arguably, research scientists trained within a well-established disciplinary matrix (Kuhn, 1974/1977) may be less aware of the basis for some of these steps in their research than social scientists who may find every assumption challenged by peers, teachers, reviewers and examiners.

At various points in a research project, decisions are made based on one's understanding up to that point (e.g. about the nature of what is being studied, based on prior reading; about what kind of knowledge it is possible to obtain in research, based upon the conceptualised nature of what is being studied; about what methodology might be appropriate, based upon the understanding of the kind of knowledge that is possible; and so forth). These are, or should be, all logical decisions.

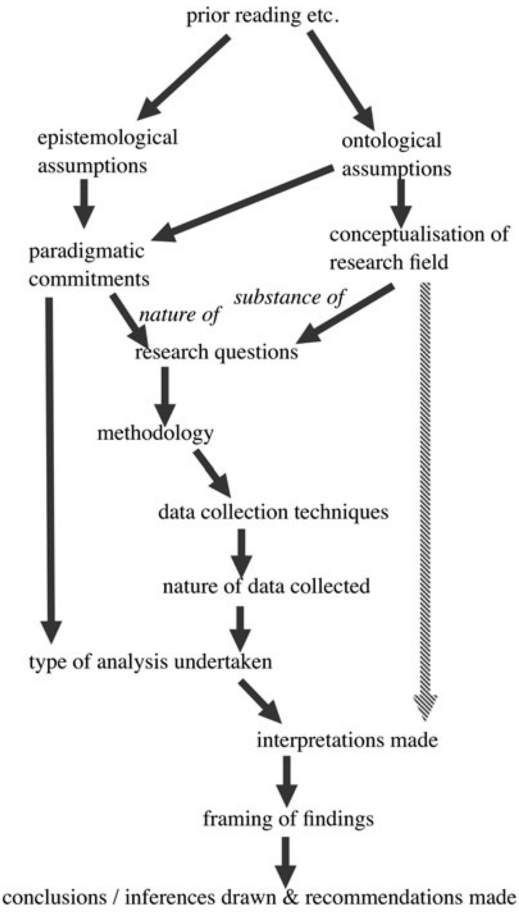


Fig. 3.3 The research process – a logical flow of decision-making

Is the Scientific Paper a Fraud?

However, logical decision-making gives no assurance that research will go as planned. Peter Medawar, the Nobel laureate quoted earlier, complained that scientific reports offer a very tidy account of a process that is actually often anything but tidy. Moreover, he suggested that the format of most scientific papers represented 'a totally mistaken conception, even a travesty, of the nature of scientific thought' (Medawar, 1963/1990, p. 228).

In particular, Medawar criticised the way research reports are based around an inductive model of scientific work, which underplays the role of the creation of scientific hypotheses,

> . . . the scientific paper is a fraud in the sense that it does give a totally misleading narrative of the processes of thought that go into the making of scientific discoveries. The inductive format of the scientific paper should be discarded. The discussion which in the traditional

> scientific paper goes last should surely come at the beginning. The scientific facts and scientific acts should follow the discussion, and scientists should not be ashamed to admit, as many of them apparently are ashamed to admit, that hypotheses appear in their minds along uncharted byways of thought; that they are imaginative and inspirational in character; that they are indeed adventures of the mind. (Medawar, 1963/1990, p. 233)

Scientific papers focus on the 'context of justification', that is the logical argument for why what is claimed might reasonably be believed to be so. However, in doing so, they tend to ignore the 'context of discovery': the processes by which the researcher initially thought of a particular idea (Hoyningen-Huene, 2006).

In one sense, this is fine, because the main purpose of a scientific research report is to justify knowledge claims. Yet there would be no such claims or justifications without the creative process by which scientists produce their original ideas.

The Role of Creativity in Science

Creativity is certainly a central part of science, and indeed part of the expectation of the major qualification for any researcher, the Ph.D. degree, is that work should be original. Originality in this context means offering something that is new to the literature in the field concerned. The originality may be of various kinds: applying existing ideas in a novel context; developing new instrumentation or analytical techniques; offering a new synthesis of disparate literature and so forth. However, the key is there needs to be some novelty. Arthur Koestler argued that science, art, and humour, all relied on the same creative processes of bringing together previously unrelated ideas into a new juxtaposition.

> Creativity in science could be described as the art of putting two and two together to make five. In other words, it consists in combining previously unrelated mental structures in such a way that you get more out of the emergent whole than you have put in. This apparent bit of magic derives from the fact that the whole is not merely the sum of its parts, but an expression of the relationship between its parts; and that each new synthesis leads to the emergence of new patterns of relations – more complex cognitive holons on higher levels of the mental hierarchy. (Koestler, 1978/1979, p. 131)

When Lise Meitner and Otto Robert Frisch puzzled over results from Meitner's laboratory which suggested nuclear processes leading to daughter nuclei much smaller than the parent nuclei (which did not fit any of the then-known decay processes), they proposed the possibility of nuclear fission on the basis of an analogy between a heavy nucleus and a liquid drop,

> On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops. (Meitner & Frisch, 1939, p. 239)

Meitner had fled Germany to escape Nazi persecution, leaving her experiments in the hands of her colleagues Otto Hahn and Fritz Strassmann. However the 'laboratory of the mind' (Brown, 1991) goes with us wherever we are, and Meitner was able to think of a novel explanation for the results her colleagues reported.

Regardless of whether one is a naive realist (seeing science as capable of producing a true account of the world) or more of an instrumentalist (accepting that positivism is an unrealistic goal, and considering science as about developing models that fit well enough to what we experience as reality to work for human purposes), there is a need for someone to produce the idea that will then be tested to see if it is how the world is, or at least how we can currently best model the world.

Yet how we have such novel ideas is not well understood. In logical thinking conclusions are in a sense already implied by the premises, and so the logical work to be done is routine if sometimes difficult. However, creative thinking means coming up with something that goes beyond the information available; that is, something that is not logically justified (but of course can subsequently be put to the test).

In logical thinking, the thinker is aware of what they are doing. In creative thinking there is no set procedure or set of steps to follow – although of course various heuristics and techniques have been applied to encourage creative thinking (Bruner, 1961/1963) – rather the processing occurs subconsciously and an idea just appears in consciousness (Taber, 2008a).

The Nature of the Creative Process

Indeed, there are many stories of how creative thinking is best supported by relaxed distraction. Whether focused concentration actually interferes with the creative process, or simply makes one aware of the lack of apparent progress, there are many reports of how creative ideas arrived in the mind only when the problem was not being consciously considered. An early, and well-known, example concerns Archimedes. Set the task of finding a non-destructive way of determining the purity of a gold crown, Archimedes is reputed to have solved the problem as he took a bath. Supposedly, as he lowered himself into the bath, Archimedes had the insight that if the gold provided to the jeweller had been adulterated with another metal, then although it would have the expected mass (as the jeweller would have substituted for the same mass of gold to misappropriate some of the original gold), the crown would have a different density, and would displace a different volume of water than the same mass of pure gold.

Perhaps Archimedes had already developed the first part of this argument, and was puzzling over how he would measure the density. Living at a time before the establishment of the modern scientific paper, Archimedes does not seem to have felt the need to disguise the origin of his insight; and the analogy between the familiar context and the target problem ('if water splashes out when I get in a full bath, then…') is of interest here, as analogy has been proposed as one major source of creative ideas in science (Muldoon, 2006).

Another famous example concerns the chemist Friedrich August Kekulé who suggested a viable molecular structure for the compound benzene. This had been a question of interest because although a formula had been established, no feasible structure had been suggested which fitted (i) the formula, (ii) the known structural patterns of organic chemistry and (iii) the actual properties of the substance itself. Kekulé solved the problem by suggesting that rather than being some form of chain, like other structures accepted at that time, the structure was actually a ring. Kekulé later claimed that the solution had come to him whilst he was dozing: that he had an image of a snake biting its own tail, and woke up to realise that image transferred to a chemical structure that solved the problem,

> I turned the chair to face the fireplace and slipped into a languorous state. Again atoms fluttered before my eyes. Smaller groups stayed mostly in the background this time. My mind's eye, sharpened by repeated visions of this sort, now distinguished larger figures in manifold shapes. Long rows, frequently linked more densely; everything in motion, winding and turning like snakes. And lo, what was that? One of the snakes grabbed its own tail and the image whirled mockingly before my eyes. I came to my senses as though struck by lightning. (Translation quoted in Rothenberg, 1995, p. 425)

There seems to be some question over the precise circumstances of this insight (as several versions seem to be in circulation), and it has been suggested that Kekulé himself may have told variations of the story, but it has none-the-less passed into scientific folklore.

Another case would be that of the Nobel laureate Barbara McClintock. McClintock worked on plant genetics and is most famous for proposing the notion of 'jumping genes'. McClintock's way of working was to be involved with her plants in the field as well as in the laboratory studies – so the tissue she examined under the microscope came from plants she knew and had watched grow (Keller, 1983). She claimed that her long close association with her material led to a level of understanding that was based on thinking that was not fully conscious. She developed what her biographer, Evelyn Fox Keller, called 'a feeling for the organism'.

This is the use of intuition in science. Intuition should not be confused with instinct, genetically coded behaviours; for intuition can be developed by extended familiarly with a target domain. It can be understood in perfectly natural terms, as part of the way the brain learns over time to interpret patterns in information. However it works at a subconscious level: at the level between the body receiving sensory information and presenting percepts to conscious (Taber, Forthcoming). As such pattern-recognition processes are subconscious they are fast and automatic, which is very useful when they are accurate, but also gives scope for them to mislead us. Such processes have been hypothesized to be important in the development of alternative conceptions in physics (diSessa, 1993) and chemistry (Taber & García Franco, 2010).

McClintock was aware that her brain 'integrated' information prior to her consciously being aware of the results, and found the inability to elucidate the process by introspection frustrating on the occasions when her results contradicted her intuitions. However, generally she was comfortable relying on this process as part of her scientific thinking,

> I read the paper and when I put it down I said, 'This can be integrated'. My subconscious told me that. I forgot about it, and about three weeks later I went into the laboratory

> one morning at the office. I said ‘This is the morning I’ll solve this’. (Quoted in Beatty, Rasmussen, & Roll-Hansen, 2002, p. 282)

Although, as Medawar points out, most scientists do not tend to report on this aspect of the scientific process of discovery in their research reports, this is a key part of science. Michael Polanyi (1962), the chemist and philosopher, wrote about the importance of tacit knowledge in the work of scientists, recognising that this was a critical feature of scientific work. Although this can be considered a form of knowledge, it may well be processed in non-verbal forms in brain circuits that are encapsulated, and only present the outputs of processing to consciousness (Karmiloff-Smith, 1996). Unlike the scientific paper, the scientific intuition ignores the context of justification and only offers us the discovery.

It is this tacit knowledge, this subconscious cognition supporting intuition, which offers the scientist a feel for what to do next when there is no obvious logical basis for decision-making. Like Koestler, Myers argues this is akin to artistic processes,

> Creativity in science shares with the arts many of the same impulses: self-expression, an aesthetic appreciation of the universe, and a search for truth and a view of reality. . .It is ‘imagination in search of verifiable truth’, requiring a ‘feeling for the order lying behind the appearance’. . .Scientific revelation brings order to chaos. (Meyers, 1995, p. 763)

However, whereas the artist can simply act on the impulse and produce work for the field to critique later; the scientist uses such impulses as starting points for work that will have to be logically justifiable before it is presented to the scientific community.

Einstein is commonly quoted as suggesting that ‘the intuitive mind is a sacred gift and the rational mind is a faithful servant. We have created a society that honours the servant and has forgotten the gift’. Einstein was one of a number of scientists who have described how much of their creative thinking was imagistic (Miller, 1986). Nersessian (2008) has described how scientists form mental models, often represented in images, which act as mental simulations that can be run so that the outcomes can be compared with the target phenomenon.

Kind and Kind review the role of creativity in science education, and argue that

> imagery and imagination are important skills for scientists. When developing new theories they use the ability to imagine and visualise physical phenomena and ‘play’ with possible outcomes. Examples include simple analogies, as when Einstein, while working out the general theory of relativity, imagined what it would be like to ride on a ray of light and Faraday visualised electromagnetic field lines. (Kind & Kind, 2007, p. 22)

The Role of Creativity in Learning Science

Creativity is clearly then important in the development of the public knowledge of science, because it is essential to the discovery process, even if formal research reports are focused on the context of justification, and leave the context of discovery as material for anecdote, after-dinner speeches or memoirs. As creativity is so essential to science, any authentic science education should reflect that.

Creativity and Learning About NOS

Teaching students about NOS has often focused on enquiry processes, which in practice has often meant the testing of hypotheses. We can ask the student to suggest the hypothesis to be tested, and the methodology to be used, and that potentially is a creative process. That might be one area where US science education tends to fare somewhat better than UK science education, at least when inquiry teaching is done well (Lawson, 1985).

Under the English National Curriculum that was in place during the last decade of the twentieth century and much of the first decade of this century (DfEE/QCA, 1999), forming a hypothesis became a step in scientific 'inquiry' rather lacking in any genuine creativity. The formally assessed practical work, which contributed marks toward grades in the high-status school leaving examinations, degenerated into exercises that were devoid of any real notion of creativity, or spirit of inquiry (Taber, 2008b).

Table 3.1 gives an impression of the practice that developed under that curriculum regime. Teachers would set up practical exercises where nominally the student chooses what to test. However, the equipment and materials available often limited rationale choice to one of a small number of well-defined variables. Moreover, the 'enquiries' were usually related to demonstrating well-established principles that were specified in the examination syllabus, class notes and textbooks. The students effectively had to show they could demonstrate accepted relationships. The actual level of choice available to students was minimal, which is unfortunate, as choice seems to be highly motivating to students in science classes (Taber, 2007a).

Table 3.1 Caricature of the type of practical exercises commonly used in English schools to assess Scientific Enquiry skills under the 1990–2007 curriculum

Nominal focus of scientific enquiry	Factors influencing electrical resistance	Factors influencing rates of reaction
Materials provided include	Test circuit Meters Samples of copper wire of different lengths and radii	Magnesium ribbon Hydrochloric acid of concentration 2 mol dm^{-3}, 1 mol dm^{-3}, 0.5 mol dm^{-3} Stopwatches, thermometers Glassware, Bunsen burners
Background knowledge	Resistance is proportional to length Resistance is inversely proportional to cross-sectional area	Rate of reaction usually increases with increased temperature Rate of reaction is proportional to concentration
To investigate	Effect of length of copper wire on its resistance; or Effect of diameter of copper wire on its resistance	Effect of temperature of acid on time taken for length of magnesium ribbon to completely react; or Effect of concentration of acid on time for length of magnesium ribbon to completely react

To be fair, when the decision to introduce assessed practical work in science as part of the national examination system was taken, many teachers initially responded by generating imaginative and interesting ideas for practical work. However, as often happens with high-status testing, over time it was found students got better marks if the teaching becomes more focused on supporting students in meeting the criteria, rather than learning about science. For example, the way marking schemes were set up, any 'inquiry' that did not produce results suitable for plotting a line graph would be ineligible for scoring full marks, so it is understandable that teachers came to channel students so strongly. Teachers understandably did what they could to maximise examination results that would be used to select students for college courses, to judge teacher effectiveness and to rank schools in public 'league tables'. However, such restrained 'scientific inquiry' seems unlikely to whet scientific curiously and creativity:

> Never mind thinking up paradoxes Albert, go back to your photoelectric work: that gave a nice straight line graph. Well, yes, that's an interesting idea Charles, but you have a rather eclectic collection of data: maybe you could plot average beetle mass against latitude? You only have an hour for this work Marie, so perhaps you should stop trying to isolate new elements, and help Pierre obtain a decay curve. Please stop doodling Richard, if you can't think of anything to measure you may as well give up on passing science and concentrate on practicing your drumming.

Creating Scientific Conceptions

Yet that is not to suggest that students do not naturally show creativity in their science lessons. The vast literature on alternative conceptions shows that learners have collectively generated immense catalogues of alternative ways of thinking about scientific concepts. Some of these conceptions seem to be common across many learners, but others are idiosyncratic. One student I worked with had misconstrued the basic formalism used in chemistry to indicate the charges on ions: yet managed to almost complete her college chemistry course finding ways to interpret teaching, reading and her peers' comments to be consistent with her own idiosyncratic formalism (Taber, 1995). Indeed, the matter was only diagnosed because 'Annie' volunteered to take part in a sequence of in-depth interviews exploring her understanding of chemical topics.

Given any class, in any school or college, students will be able to offer a wide range of ideas about light, sounds, plants, energy, acids, planets, the weather and so on. Some of these ideas will match scientific ideas, even when there has been no formal teaching of the topic. Often, however, these ideas will be inconsistent with science, even after formal teaching. Sometimes students will strongly believe their ideas – even when they flatly contradict accepted science. Other times students will offer a range of alternative ideas that they have considered, without necessarily being committed to any of them being right. Here we have a vast resource for creative science teaching and learning. Moreover, the alternative nature of many of those ideas need not be seen as inherently problematic: indeed, rich conceptualisation seems to be a useful prequel to later effective learning of the science (Ault, Novak, & Gowin, 1984). In science learning, as in science, entertaining a range of ideas would seem be preferable to having a strong attachment to one.

Of course it may be argued that students, especially in school, are hardly likely to come up with truly original ideas – and that indeed few scientists come up with highly significant new ideas. But in education we should be interested in creativity in personal knowledge, not by the standards of public knowledge. A student that I interviewed invented the idea (but not the label, of course) of van der Waals' forces between molecules as she answered one of my questions. This was a creative act of bringing together several existing ideas to form a novel synthesis – and no less impressive because Johannes Diderik van der Waals had beaten her to it.

My informant did not invent the idea of van der Waals' forces from first principles – she already had a lot of the background knowledge in place, but as she worked through her thinking, she brought this knowledge into a new juxtaposition, and made, as Koestler would have said, a new bissociation – new at least for her. That is the creative act – the same creative process that leads to novel ideas in science where professional scientists also build upon on their background knowledge and understanding to posit genuinely new ideas.

We all learn through an iterative process, and create novel ideas by forming new constructions from the existing conceptual resources we have available. As Fig. 3.4 suggests, students who come to science classes have already been undertaking this construction process over many years, drawing upon a range of sources.

The different sources have variable reliability, and are all interpreted in terms of what we understand to date: an accepted misinterpretation may later be corrected, or may simply be the basis of further misinterpretations of related learning. 'Sandra' logically deduced that the stars were much smaller than the sun; because she knew they were much closer; because she knew astronauts had passed them on the way to the moon (Taber, 2010a). The starting point for this chain of logic was a false premise, apparently a misinterpretation of footage she had seen of the view through spacecraft viewing ports.

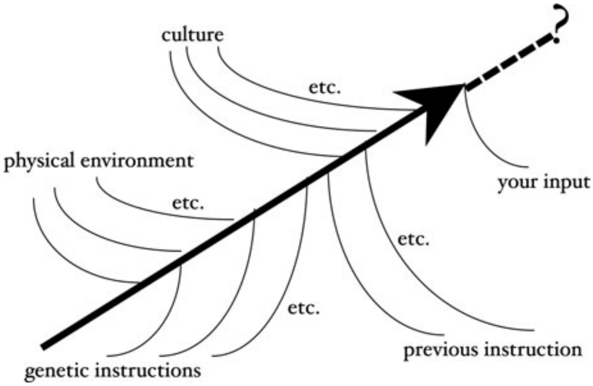


Fig. 3.4 The teacher is just one more source in the learner's ongoing iterative knowledge construction project

Building Upon the Learner's Creativity

It has been suggested that constructivist teaching schemes (Driver & Oldham, 1986) that begin by asking pupils to suggest ideas to explain phenomena are likely to encourage the development of alternative conceptions. Perhaps that is sometimes the case; but, if so, that's a sad indictment on the way ideas are treated in science lessons. In science, ideas are seen as possibilities for imagining the world, not absolute accounts of what must be. That must become the case too in science lessons.

This brief consideration of creativity in science and learning has suggested a number of important propositions

- creativity – forming new ideas – is a major part of science
- learning is intrinsically a creative process
- students create all sorts of ideas about the world

This might suggest that we should be able to build creativity into science education. That would be good not only because creative scientists are valuable in society, but because creative learning is engaging and so motivating (Csikszentmihalyi, 1988).

Going by the wide range of alternative conceptions reported in the literature, every classroom offers a potential wealth of alternative ideas to be explored and tested in science lessons. Yet it has also been widely argued that students do not seem to be very good at subjecting their ideas to critical examination and testing – understandably, perhaps, as this involves (a) overcoming the natural tendency to trust the cognitive apparatus we usually rely upon to make sense of and act meaningfully in the world, and (b) adopting, for argument's sake, a different perspective. Consequently, constructivist approaches to teaching may be seen as encouraging an intellectual free-for-all that is high on imagination but lacking disciplined analysis.

Perhaps this is often so, but if my account of how school science must appear to students reflects common experience, then we have little reason to expect anything different. Shifts between alternative, inconsistent accounts that seem to be based on little more than 'which description works here' do not encourage the critical attitude. 'Inquiry' into the effects of the variables students are already expected to have learnt about does little to teach open-minded approaches to experimentation and evidence. Practical work that requires students to draw generalised conclusions of universal applicability by testing single examples drawn from broad classes are not designed to give insight into the context of justification of scientific ideas.

Teachers demonstrate much creativity in getting across some flavour of abstract scientific ideas, for example using metaphor – such as atoms that share electrons – or more explicit analogy – particles which, like people, huddle up in the cold, and spread out when things are getting hot. These creative processes reflect the approaches used by scientists (What if the nucleus is like a liquid drop? What would happen if I could sit on a beam of light?), but students will not appreciate that if the metaphors and analogies are presented *as if* realistic accounts of the world.

Courting the Handmaiden

Bringing together these considerations about creativity in science and science teaching; the creativity inherent in learning; and the tendency for students to assume science and science teaching is meant literally and realistically; suggests some directions for improving science education.

Science teachers need to celebrate the creative aspects of science – the context of discovery. They should emphasise how scientific models are thinking tools created by scientists for exploring our understanding of phenomena; how teaching models are speculative attempts to 'make the unfamiliar familiar' by suggesting that 'in some ways it's a bit like something you already know about'; and in particular how scientists always have to trust imagination as *a source* of ideas that may lead to discovery. However, it is equally important that the creative act is always tempered by critical reflection. Scientific models have limitations; teaching models and analogies may be misleading; and all of us have to select carefully from among the many imaginative possibilities we can generate if we seek ideas that help us understand rather than just fantasise.

Science should not be taught as if a 'rhetoric of conclusions', but rather as the offspring of as a marriage between the creative impulse and the logical evaluation of ideas against evidence. There will be tensions in the marriage between the expansive potential of imagination, and the restrictive constraints of logical analysis. However, creativity has to be understood as an equal partner, and not just as a light distraction to break up the serious scientific work. The logic of justification depends upon the source of discovery for its material. We can give ourselves permission to let the imagination reign free, as long as we know how to then evaluate what we create.

So there are two aspects to the recommendations being suggested here. Firstly, it is vital for science education that we are more explicit about the nature of the ideas we discuss in science classrooms: whether well-established and widely verified scientific principles; scientific models of limited application; the teacher's creative attempts to make abstract ideas concrete, relevant or familiar; or the students' own creative attempts to make sense of experience and teaching. All such ideas, whatever the source – scientist, teacher or student – are due respect as creative products worthy of consideration. However, all such ideas, regardless of source, must be tested against evidence, and their application justified. Inevitably most of the students' ideas will need to be at least modified – just as scientists' ideas usually evolve, and have to survive competitive selection, before they become public. But that does not negate the importance of the creation of those ideas. Science does not proceed without new ideas to test; and learning does not proceed without new potential ways of understanding to explore.

So once we can overcome the notion of science being about 'facts' and teach it as primarily about ideas – thinking tools, that are often interim and suboptimal – we will be in a position to encourage students to see science as about a process of generating and then testing ideas. *Then* we can shift science education away from being understood as learning a catalogue of previously discovered facts, to being at its heart a process of exploring and evaluating ideas that inevitably have to be created anew in each learner. This certainly does not underplay the context of justification, but suggests that justification only makes sense in the context of the imaginative discovery of possibilities. Then we can acknowledge and celebrate the centrality of the creative process in the science classroom: not just as the handmaiden to logic, but as its true partner, without which science is not complete.

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Chapter 4
The Bounded Nature of Science: An Effective Tool in an Equitable Approach to the Teaching of Science

Sherry A. Southerland, Barry Golden, and Patrick Enderle

The necessity for the public understanding of science and thus, effective teaching of science, has never been more prominent, as science knowledge and the breadth of public issues to which it applies continues to grow. We do not have to look too far to see how understanding science can directly impact our lives in a myriad of ways, including health and environmental concerns, as described in the following snippets of survey data:

- "Persons with lower socioeconomic status (SES) have disproportionately higher cancer death rates than those with higher SES, regardless of demographic factors such as race/ethnicity." (American Cancer Society, 2010, p. 38)
- In recent years, HIV infection rates have risen for some demographic groups (including gender and ethnicity combinations), while declining for others. (Centers for Disease Control and Prevention, 2010)
- The rates at which diagnoses were made for respiratory ailments and other organ disorders, including diabetes, were severely disproportionate for different demographic groups. (Pleis, Lucas, & Ward, 2009)

Yet, the impact of science on our lives broadens beyond an individual focus to encompass challenges and issues on a national and global scale.

- "Between 2004 and 2008, the proportion of Americans expressing 'a great deal' or 'a fair amount' of worry about the quality of the environment increased from 62% to 74%. Nonetheless, when asked to name the country's top problem in early 2009, only about 2% mentioned environmental issues." (National Science Board [NSB], 2010, p. 76)
- ". . . 44% of Americans indicated they had not heard much about GM (Genetically modified) ingredients added to foods to make them taste better and last longer. However, 87% believed that these foods should be labeled and 53% expected

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that it was ‘not very likely’ or ‘not at all likely’ that they would buy food that was labeled as such.” (NSB, 2010, pp. 7–40)
- “. . . 72% of Americans say that the world is likely to experience a major world-wide energy crisis by the end of the next four decades. . .two-thirds (66%) say the earth will definitely or probably get warmer over this period; just 30% say this definitely or probably won’t happen.” (Pew Research Center, 2010, p. 6)

As the products of science continue to permeate throughout our daily lives, there exists ever-expanding divides in the public perception of science, portending troubling outcomes if not addressed. These divides involve both understanding of science and perception of the scientific enterprise.

- In responding to a 12-question survey regarding basic science knowledge, “More men (36%) than women (28%) were found to be in the high knowledge category, and whites (37%) were far more likely than African Americans (10%) to fall into the high knowledge group.” (Pew Research Center, 2009, p. 51)
- While there is much scientific consensus regarding such issues as evolution and climate change, much of the American public is either in disagreement or unaware of scientific consensus. (Pew Research Center, 2009, p. 40)

These trends in the public perception and understanding of science manifest the continued challenge for science education in creating effective learning experiences for students, particularly those from varied cultural backgrounds. We argue that to achieve the goal of scientific literacy described in reform efforts (AAAS, 1989; Duschl, Schwingruber, & Shouse, 2007), students must be given an invitation into the culture of science, a foreign territory for many. The survey data above illustrate the idea that not only is public understanding of science critical, but that issues of equity emerge within that domain, in those differential results are seen across categories of race, gender, and socioeconomic status.

To be scientifically literate, to be able to make informed personal and societal judgments as a citizen, one must understand how science works and how those processes shape the nature of the knowledge science produces (AAAS, 1989, 1993, 2000; NRC, 1996). Science education, then, should focus both on the knowledge that science produces as well as “knowledge about science” (Duschl, 1990; Hodson, 2009). This “knowledge about science” includes understanding the nature of scientific inquiry and how those processes influence the nature of the knowledge produced through those processes. Hodson (2009) suggests the representation of knowledge *about* science has the potential to influence how students learn scientific knowledge, their willingness and ability to analyze knowledge claims, even their career choices. Indeed, science educators will continue to fail in realizing the goal of a scientifically literate citizenry should they not provide all students with an understanding of the nature of science.

In this chapter, we focus our efforts on highlighting an often overlooked aspect of the nature of science, its bounded nature, and we argue that appropriate emphasis on this characteristic of scientific knowledge and the nature of the inquiry that accounts for this characteristic can be a useful tool in supporting students' willingness to engage in science and the development of their scientific knowledge. For this argument, we draw on three broad areas of scholarship: learning theory, equitable science instruction, and nature of science. It is well accepted that science education should focus both on the knowledge that science produces as well as "knowledge about science." Likewise, we recognize that learning science is a difficult process that requires the actions of an engaged, active learner. Learning is understood to be influenced by a host of extra-cognitive factors, such as motivation, interest, emotions, belief/acceptance, even identity. Equitable science instruction suggests that teachers should be aware of who they are teaching as well as knowing the critical intersections between science, school science, and the cultural backgrounds of the students themselves. Drawing from these three lines of inquiry, in this chapter we argue that the bounded nature of science—the idea that science is limited in its scope by its reliance on methodological naturalism—is an important tool in the teaching of science. Through the explicit teaching of how science is bounded by its nature, we argue that teachers can appropriately situate science as nonthreatening to students' religious or cultural worldviews, thus fostering students' willingness to engage in scientific practices as it enhances their science learning.

Learning Theory

In science education, we've long recognized that meaningful learning of science is a difficult process that requires an active, involved learner. A learner's prior knowledge shapes the manner in which she comes to understand new constructs and acquires new knowledge. We also acknowledge that particularly influential components of that prior knowledge—alternative conceptions—stand in the way of students' construction of a scientifically valid understanding of a scientific construct (Wandersee, Mintzes, & Novak, 1994). This emphasis on prior knowledge in general, and alternative conceptions specifically, is particularly keen in evolution education, as a vast number of researchers focusing on the learning of microevolutionary processes have described the manner in which alternative conceptions influence the manner in which students come to understand evolution (Bishop & Anderson, 1990; Brumby, 1984; Nehm & Schonfeld, 2007; Sinatra, Brem, & Evans, 2008). An understanding of prior knowledge and alternative conceptions is also salient regarding the learning of climate change, with some researchers finding that students have poorly constructed frameworks for understanding key components such as radiation (Boyes & Stanisstreet, 1993; Koulaidis & Christidou, 1999; Shepardson, Niyogi, Choi, & Charusombat, 2009) and conflation of the greenhouse effect and/or the ozone hole and global warming (Andersson & Wallin, 2000; Boyes, Chuckran, & Stanisstreet, 1994). Other authors have found that students have difficulties in interpreting key sets of data used to buttress global warming (Shepardson et al., 2009; Golden & Grooms, 2010). The vast work conducted in some conceptual arenas, and emerging scholarship in others suggest that it is important to recognize that students' learning in many areas of science is difficult, not just because of political or social conflicts, but because many aspects of this theory run counter to our "every day" ways of understanding and reasoning about the world that are reinforced by our daily experience. In this section we offer a brief review of the literature on factors that influence students' science learning.

Affect and Learning

Although the early work in students' alternative conceptions has been fruitful in terms of allowing us to understand aspects of student learning, in recent years, there has been a growing interest in more deeply investigating the role affective constructs play in shaping student learning (Alsop, 2005; Sinatra & Pintrich, 2003). Affective constructs include (but are not limited to) emotions, motivation, attitudes, beliefs, and acceptance of the validity of a knowledge claim. While many of the models of conceptual change address the role prior knowledge and alternative conceptions play in shaping learning, they also acknowledge a much greater role for affective constructs in shaping what is learned, than what had been previously described (Dole & Sinatra, 1998; Feldman, 2000; Gregoire, 2003; Strike & Posner, 1992). For instance, as discussed by Posner, Strike, Hewson, and Gertzog (1982), "an individual must have collected a store of unsolved puzzles or anomalies and lost faith in the capacity of his current concepts to solve these problems" before learning can occur (p. 214). This loss of "faith" in a current conception is an essential component of many models of conceptual change. Both Dole and Sinatra's (1998) and Gregoire's (2003) work suggest that without some sort of dissatisfaction with a current conception, the learner will not deeply engage or systematically process a new conception; thus, without the affective construct of dissatisfaction, long lasting change of conceptions is not possible.

Clearly, affective considerations play a role in shaping a learner's learning or relearning of a knowledge claim, but how might some of these constructs influence the learning of personally controversial science? The notions that may come first to mind include belief and emotions, but educational researchers as well as the National Academy of Sciences (1998, 2008) contend that student epistemological beliefs—what they take to be knowledge and evidence as well as their expectations of scientific knowledge—are also influential in learning about controversial topics.

Various models of conceptual change require that the learner contrast their current conception with the newly introduced one. Strike and Posner (1992) describe that unless the new conception addresses problems that the original conception does not, unless it is found to be a more robust explanation, the new conception will not replace the original idea. In short, learning does not occur. We envision something like this operating when students approach a perceived controversial theory in the classroom. Students may quickly examine the new idea, but unless they find some sort of difficulty with their current ideas, the controversial theory will not be seriously considered (Dole & Sinatra, 1998). Thus, the degree to which learners find conceptions related to the topic "believable", or the best scientific explanation of the phenomena currently available (Smith & Siegel, 2004), is linked to their willingness to consider the content, deeply process the ideas, and meaningfully learn the material.

Acceptance Versus Belief

If a student approaches the classroom with a belief that some aspect of science is a faulty explanation that conflicts with her own religious or cultural views of the world, many theorists (and classroom teachers) would suggest that the learner's beliefs will prevent her from deeply engaging with the material. The argument then becomes, if a student does not "believe" in science, s/he will most likely be precluded from developing a scientific understanding [See Smith (2010) for a discussion of belief versus acceptance]. For instance, there is substantial support for the argument that acceptance is critical to developing understanding of evolution, as researchers have found a close association between acceptance of evolution and understanding of the theory (Cobern, 1994; Meadows, Doster, & Jackson, 2000; Nadelson & Sinatra, 2009; Scharmann, 1990; Smith, 1994).

Other theorists have found evidence of both quantitative (Bishop & Anderson, 1990; Brem, Ranney, & Schindel, 2003; Deniz, Donnelly, & Yilmaz, 2008; Demastes-Southerland, Settlage, & Good, 1995; Lord & Marino, 1993; Sinatra, Southerland, McConaughy, & Demastes, 2003) and qualitative natures (Demastes-Southerland, Good, & Peebles, 1995, 1996) with which to question that connection between acceptance and belief. Certainly, it would be difficult to accept a construct that a student does not understand. In one last caveat, it seems that the relationship between acceptance of a controversial topic and understanding depends on the *depth* of knowledge a student has. For instance, Southerland and Sinatra (2003) and Nadelson and Sinatra (2009) contend that as learners gain more understanding of evolution, the association between their knowledge and acceptance intensifies.

Emotions

Beginning with the revision of the original conceptual change theory in 1992 by Strike and Posner, models of conceptual change have become more "hot," meaning they recognize affect—particularly emotion—as playing a significant role in the process. Gregoire (2003) is particularly explicit in this regard in her conceptual change model as she describes the influence of emotions on a learner's personal significance (the extent to which the concept involves the self). In Gregoire's model, emotions shape the manner in which the learner evaluates new knowledge claims. In short, if the claim is perceived to be a personal threat, learners are much less likely to adopt a new idea. Thus, it seems as though consideration of a controversial topic in science may carry with it a particularly negative emotional connotation in students, something that may limit students' willingness to deeply consider and process the theory.

Learning Dispositions

General tendencies toward thinking and learning, referred to as learning dispositions, seem to play an important role in shaping student learning of evolution. Stanovich (1999) defines dispositions as "relatively stable psychological mechanisms and strategies that tend to generate characteristic behavioral tendencies and tactics" (p. 157). Interpreted in the context of learning dispositions, these tendencies are related to how learners engage in knowledge acquisition and development of understanding. One of the learning dispositions that have been found to play a role in learning about evolution is *belief identification,* which is the degree to which an individual values stasis in their personal beliefs and believes that changing beliefs is a sign of weakness or disloyalty (Sa, West, & Stanovich, 1999). A study by Sinatra et al. (2003) of 93 college undergraduates found that *belief identification* was strongly related to students' knowledge of evolution. In this study, students who viewed belief change in a favorable light were more likely to understand evolution. Likewise, learners who were found to have greater capacities for both open-mindedness and degree of comfort with ambiguity were more likely to understand evolution. Again, generalizing these findings, there are some learning dispositions that seem to play a role in shaping how students come to understand and accept controversial content.

Religious Commitment

Linked to some of the affective categories previously discussed, various researchers have found a relationship between students' religious beliefs or commitments and their willingness or ability to learn about science that contradicts those beliefs (Nadelson & Nadelson, 2009; Nadelson & Sinatra, 2009). Fundamentalist religious beliefs have long been recognized as a largely negative influence on a student's understanding of evolution (Smith, 2009). This contradiction may be explained by the learning dispositions typically associated with this subset of religion, which tend to be contrary to open-mindedness, change in beliefs (belief identification), and comfort with ambiguity. For instance, creationist students tend to "exhibit lower motivation, increased anxiety, less interest, and more emphasis on grades than learning" during instruction in evolution (McKeachie, Lin, & Strayer, 2002). Indeed, Francis and Greer (2001) have found a negative correlation between creationist attitudes and science. Nehm and Schonfeld (2007), in their examination of teachers learning about evolution during a college course, describe that students' "religiosity"—the degree to which they place importance on the role of religion in their lives—more strongly predicts understanding of microevolution than their prior knowledge on the topic. How can we understand this? As Smith (2009) describes, "Certain religions may, in fact, teach precepts that directly oppose the tenets of evolution, e.g., the fundamentalist belief in a literal translation of the Bible and thus of a young-earth creationist" which are ideas that are in direct contrast to the current scientific understanding of the related phenomenon.

Epistemological Beliefs

One of the most prominent public reactions to any science that is seen as fundamentally contradictory to long-held religious convictions is "It's only a theory" (Bhattacharjee, 2008). Much is embedded in this phrase: the notion that a theory is a weak construct, an ephemeral knowledge claim, has limited explanatory power, and has substantially lower worth than more valued knowledge constructs. This kind of phrase serves as a representation of personal epistemology and its role in influencing the learning of evolution. Students' personal epistemological beliefs include their views of the "origin, nature, limits, methods, and justification of human knowledge" (Wood & Kardash, 2002). While we categorize *beliefs* as part of the more affective influences on learning, we do so with some hesitation, as clearly some aspects of a personal epistemology is more cognitive and developmental in nature (and thus may be more open to change than a belief system).

Research aimed at studying epistemological beliefs has focused on several aspects of students' epistemic perceptions, including their propensity to seek single answers, their reluctance to criticize authority, their tolerance for ambiguous information, their dependence on authority for information and interpretation, and their perceptions of knowledge as certain (Schommer, 1990). The work of Sinatra et al. (2003) in this area suggests that epistemic beliefs may be more influential when the construct in question is highly controversial to the learner (e.g., human evolution) and less influential when the material is less controversial (e.g., photosynthesis, animal evolution). Thus, the role epistemology plays may vary according to the nature of the content to be learned.

Summary on Influences on the Learning of Controversial Material

As has been discussed, a wealth of research suggests that learning is an active process that is influenced by a host of rational and extra-rational factors (Pintrich, Marx, & Boyle, 1993; Strike & Posner, 1992). While original formulations of the conceptual change model (Posner et al., 1982)—a model that has been particularly productive in helping researchers understand the ways in which learners come to learn and relearn about major, organizing conceptions—more recent work has pushed past the rational, logical, strictly cognitive confines of this model (Alsop & Watts, 1997; Pintrich et al., 1993; Southerland, Johnston, & Sowell, 2006; Venville & Treagust, 1998). Indeed, these authors and many others in the research communities of both science education (Alsop, 2005; Lee & Anderson, 1993) and educational psychology (Pintrich, 1999; Sinatra, 2005; Sinatra & Pintrich, 2003) describe a "warming trend" in conceptual change research in which goals, emotions, dispositions, and motivations are understood to interact with cognitive constructs to play a significant role in shaping learning.

Given this warming trend, the interplay between religiosity, beliefs, acceptance, personal epistemology, learning dispositions, and prior knowledge make apparent the complexity and challenge associated with helping students come to understand the science that may conflict with their *everyday* ways of understanding the world. We provide this review of the more recent literature on conceptual change to call attention to the fact that learning is not solely rationally determined. The research community has recognized what science teachers have long known, that a learner's affect and emotions significantly influence the learning that can occur. It is not just what the learner knows that determines what she learns in a classroom, but how that learner views her knowledge (sure or tentative), her views of contradictory evidence, her willingness to engage deeply with a complex issue, her view of herself as a capable science learner that is expected to participate and engage in the class activities, and even (or in some cases especially) a learner's emotions surrounding an aspect of science. Each of these attributes shapes how the learner engages with new information and if she processes this information deeply or superficially (Dole & Sinatra, 1998), thus directly shaping the learning that occurs.

Equitable Science Instruction

As described by Lee and Buxton (2008), the overall quality of science education in the United States is shaky at best. They identify several ways to measure this quality: scores on international and national exams, student course-taking patterns, and college majors and careers. An examination of the Program for International Student Assessment (PISA) 2006 results reveals that American of 15 year olds (the age at which the test is administered) scored at the bottom half of the participating nations in terms of students' abilities to apply their scientific knowledge (through explaining phenomena scientifically, using evidence, and identifying scientific issues) (Baldi, Jin, Skemer, Green, & Herget, 2007). These results have been consistent over the last decade. In contrast, the most recent administration of the Trends in International Mathematics and Science Study (TIMMS) reveals that while still low, the US students had lessened the gap between the US and other nations (Gonzales et al., 2008). However, these same data also point to the long-term gap in achievement between the US students from different racial categories. That gap remains when examining the National Assessment of Educational Progress (NAEP) results. NAEP results indicate that students on the reduced or free lunch program underperform compared to students who are not, and achievement gaps for African American students and Hispanic students are so large that the final achievement levels for these students are comparable to the 8th grade achievement levels for White and Asian American students (NCES, 2006).

There have been gains in the course-taking patterns of students in various demographic groups. In recent years, more African American, Hispanic, and Native American students are taking 2 years of high school science in addition to chemistry and physics, although they still lag behind their White and Asian American counterparts (Lee & Buxton, 2008; NSF, 2002). Likewise, more students of color are pursuing STEM degrees, but long-term gaps persist when comparing the STEM majors of students of color and that of White and Asian American students (National Science Board, 2010).

These findings become even more troubling when considered within the call for "science for all" (AAAS, 1989):

> Education has no higher purpose than preparing people to lead personally fulfilling and responsible lives ... The world has changed in such a way that science literacy has become necessary for everyone, not just a privileged few: science education will have to change to make that possible (pp. xiii–xvi, AAAS, 1989).

The goal of fostering scientific literacy in all students has been central to the science education community for more than two decades. However, several measures of the quality of science education indicate that in the US, scientific understanding, at least as measured by the above items, seems to continue to belong to a select few rather than the whole of our students.

A host of researchers, such as Oakes (1990), Parsons, Crystall, and Simpson (2005), Rosebery (2005), Lee and Luykx (2006, 2007), and Lee and Buxton (2008), argue that achievement gaps in science may be due to differences in how science has been taught, or the failure to adapt how science is taught to the particular needs and abilities of nonmainstream students. [Our use of "nonmainstream" follows in the tradition of Lee and Luykx (2006), who describe mainstream as referring "not to numerical majority, but rather to social prestige, institutional privilege, and normative power… mainstream students" (p. 173).] Indeed, as described by Grandy (1998) and Lee and Buxton (2008), regardless of demographic group, students who are challenged by rigorous coursework and actively engaged in order to learn science are more likely to be high science achievers. This finding lends weight to the argument that one of the central reasons we fail to teach "science for all" is due to how science is taught.

Noted earlier, accessing students' prior knowledge and related affective dimensions on a science topic before instruction becomes essential for effective science instruction. Albeit possibly over-simplistic to state, but by the time a student enters school, he already has a wealth of knowledge, values, beliefs, attitudes, and ways of looking at the world that he has developed in his culture and society. This is true even for science. Because the knowledge values, beliefs, attitudes, and ways of looking at the natural world of nonmainstream students are often different from that of their mainstream teachers, administrators, textbooks, and even the discipline of science, then nonmainstream students' essential prior knowledge and the affective components that shape it are often ignored or undervalued (Moje, Collazo, Carillo, & Marx, 2001). Thus, as authority figures privilege assimilation of mainstream attributes, nonmainstream students must sacrifice visceral elements of their deeply personal, culturally embedded identities.

This rejection of what a student knows and how s/he feels about a topic is particularly disadvantageous for science learners, as teachers are often ill-prepared to help nonmainstream students make sense of the often discontinuous world of knowledge that science provides. Because the knowledge and beliefs of mainstream students are often more congruent with that of their teachers and text, they are better supported in their learning of science. Lee and others argue that this difference, in terms of whose knowledge, language, reasoning, and affect is recognized and used to build from in the classroom and whose is not, is the central reason for the achievement gap (Lee & Buxton, 2008; Lee & Luykx, 2006, 2007).

A central construct in the literature, examining science teaching and learning of nonmainstream students, invokes the notion of *instructional congruence*. Instructional congruence describes the importance of developing congruence between a student's home culture, patterns of reasoning and language, and that of science, a culture of its own (Lemke, 1990). Because the knowledge and beliefs of nonmainstream learners are often discontinuous with science, a teacher's challenge becomes that of finding ways to bridge this discontinuity (Lee & Buxton, 2008). Finding ways to connect students' out-of-school knowledge and affect with that of science are particularly important when the culture of the student is very different from that of science. In teaching mindful of instructional congruence, the teacher acts as a sort of interpreter, helping students understand how their home knowledge, affect, or ways of reasoning are different from, or related to, what is being studied. A teacher who bases instruction on the idea of instructional congruence has the goal of *equity* in mind. (Equity describes that teachers have the same goal for students, but realize that instruction will need to be varied in order to get each student to meet that goal.)

Instructional congruence is a form of *Multicultural Science Education* (MSE) (Southerland, 2000) that describes the need to adapt instruction in order to more sensitively, respectfully, and effectively teach science *as it is traditionally defined*. In contrast, *Curricular MSE* suggests that teachers must *redefine* the epistemology of science to equate local or ethnic ways of understanding the physical world with that of western science. While both instructional and curricular MSE have the goal of more sensitive and respectful science education, one can see that they propose to achieve these goals in fundamentally different ways. Rather than struggle to redefine fundamental characteristics of science, we, along with others, argue that an appropriate goal of science teaching is to empower nonmainstream students to gaining access to the mainstream, and this is to be done through instruction that is sensitive to, and establishes congruence with, their native cultures (Delpit, 1988; Lee & Luykx, 2006).

A wide body of research has explored the way that scientific knowledge and practice is discontinuous with that found in students' home lives (Fradd & Lee, 1999; Lee, 2003; Southerland, Kittleson, Settlage, & Lanier, 2005). Thus, one important aspect of teaching science mindful of instructional congruence is the need to make explicit the rules and norms of thinking and practice within the discipline. For instance, in science this could be the need to highlight the importance of questioning, evidence, and argument in the construction of scientific knowledge—even close examination of what "counts" as useful questions, evidence, and argument within science and how these constructs may differ from what students practice at home.

African American culture retains a vestige of African tradition, known as the Bantu effect, that "emphasizes a strong oral tradition which places supreme ethnographic value on an individual's ability to communicate impressively" (Vass, 1974, p. 102 as cited in Hilliard, 2002). Classroom science discourse, which may avoid many stylistic devices, such as emphasis and gesture, can seem foreign and distant to students with these cultural roots. Furthermore, Lee (2006) has described that nonmainstream learners find the process of inquiry within science classrooms particularly difficult, as many are not exposed to a constant diet of questions in ways that white, middle-class learners are. In teaching for instructional congruence, then, the idea is not to discard the goal of effective participation in inquiry for such learners, but to understand that some nonmainstream learners may require much more scaffolding to develop inquiry skills and abilities (Buxton, 2006; Lederman, Abell, & Akerson, 2008). In a classroom in which instructional congruence is practiced, teachers help students to question and inquire without being dismissive of the cultural practices employed in their homes, allowing for students to learn to *think* and speak scientifically *when* the situation demands it (Delpit, 1988; Southerland, 2000).

Instructional Congruence and the Teaching of Controversial Aspects of Science

As described in the previous section on learning theory, it is not just what the learner knows that determines what she learns in a classroom, but how that learner views her knowledge (sure or tentative), her views of contradictory evidence, her willingness to engage deeply with a complex issue, her view of herself as a capable science learner that is expected to participate and engage in the class activities, and even (or in some cases especially) a learner's emotions surrounding an aspect of science. Because each of these attributes shapes how the learner engages with new information and if she processes this information deeply or superficially (Dole & Sinatra, 1998), each of these aspects must be considered by a teacher who is mindful of the congruence of the science to be learned and the particular learners in her classroom.

The goal of spanning the possible gap between science and a student's home culture becomes particularly difficult when the science to be learned is thought to contradict some aspect of a student's cultural knowledge. If instructional congruence requires that teachers help students think scientifically without being dismissive of the cultural practices employed in their homes, how is this possible when the science to be taught and learned is thought to contradict what a learner believes to be true?

The Bounded Nature of Science as a Tool to Achieve Instructional Congruence

There are a number of well-documented areas in which science conflicts with students' out-of-school knowledge. While the areas of conflicts vary with the population of students involved, some common examples include climate change/global warming, vaccine safety, origins of HIV/AIDS, and many other scientific and pseudoscientific topics. A great bulk of our own teaching and research has focused on biological evolution to understand these tensions.

As an example, the Gallup poll survey in the US asked individuals to respond to the statement, "*Do you, personally, believe in the theory of evolution, do you not* *believe in evolution, or don't you have an opinion either way.*" The results indicate that less than 40% of the respondents believe in evolution, which would indicate the majority of the American public (over 60%) does not acknowledge or fully accept the scientific perspective of evolution. Although the psychometrics of these polls is problematic and the choice of terms (belief versus acceptance) must be considered, the results from such public polling have been substantiated by a wealth of studies (Alters & Alters, 2001; Miller, 2008; Nadelson, 2009; Nadelson & Nadelson, 2009; Nadelson & Southerland, 2010).

Beyond a rejection of evolutionary theory, Brem et al. (2003) hint at negative emotions surrounding consideration of this topic. They describe undergraduate students (both those that accept evolution and those that do not) as perceiving there to be several "undesirable" impacts of the theory and project several possible negative outcomes associated with evolution (e.g., racism, selfishness, decreased spirituality, loss of a sense of purpose). Thus, for many students, evolutionary theory elicits a negative, emotional reaction.

Many science educators and science teachers operate as though a student's belief and emotions surrounding the topic are not factors to be targeted in instruction (Smith & Siegel, 2004). However, teachers react to students' affective responses (both perceived and demonstrated) to evolution, influencing the way teachers plan and enact instruction. Aguillard (1999) describes that 60% of Louisiana's teachers spend less than 5 days teaching evolution. This is echoed in Texas, where 55% of teachers spend less than 5 days on this topic (Shankar & Skogg, 1993). Likewise, in South Dakota, biology teachers spend a mean of 5 days teaching evolution (Tatina, 1989). Dean (2005) describes that some teachers in Alabama assign the chapter on evolution to their students, without discussing the topic. Others simply fail to even assign the chapter. In Ohio, Dean (2005) found that many teachers would not approach evolution as a unit; instead, they would teach small aspects of it sporadically throughout the year. This supports a description of evolution education in Indiana, in which one-third of the teachers surveyed devoted less than 4 days to the teaching of evolution (Rutledge & Mitchell, 2002; Rutledge & Warden, 2000).

For years, biology teachers and instructors, science educators, as well as groups such as the National Academy of Sciences, the National Research Council, and the American Association for the Advancement of Science, have recognized the difficulties of evolution education. In response, they have produced a myriad of curricular support for teachers, such as *Teaching evolution and the nature of science* (NAS, 1998) and *Understanding evolution for teachers* (http://evolution.berkeley.edu/evosite/evohome.html), as well as the recent *Science, evolution, and creationism* (NAS, 2008). One thing in common throughout each set of these materials is the emphasis paid to the nature of science in teaching about evolution. The nature of science (NOS) includes the characteristics of scientific knowledge, the epistemology of science, its presuppositions, methodological assumptions, goals, and boundaries, as well as the conventions underlying the knowledge produced through science (Lederman, 1998). This collection of ideas serves, most essentially, as a set of underlying principles describing what makes science "science" (Southerland et al., 2006). Learning science requires one to understand scientific knowledge, as well as to recognize the unique characteristics of the knowledge that science produces. This is particularly true for evolution education, in which students have a tendency to critically examine the strength of these knowledge claims. Thus, understanding evolution and its evidentiary basis necessitates understanding the nature of science. A consensus from the communities focused on this issue is that the teaching of evolution is best supported by a thorough analysis of the nature of science.

Aspects of the nature of science deemed necessary for emphasis before or as one teaches evolution include:

- the empirical nature of science (that scientific knowledge requires evidence drawn from the physical world),
- the subjective nature of science (the idea that scientific knowledge is constructed by scientists based on their sense-making from empirical evidence),
- the characteristics and relationships of theories and laws (the idea that scientific theories represent our most powerful and useful scientific explanations of the physical world, while laws represent a description of the relationships between two factors), and
- the tentative, yet durable, nature of science (the idea that because science is empirical, but subjective, we expect that scientific knowledge can and will change. But because science requires evidence and negotiation through the scientific community, we expect these changes in our most powerful theories to happen infrequently).

Although these aspects of the nature of science are part of the widely accepted consensus view of the need for NOS-based education (Abd-El-Khalick, Bell, & Lederman, 1998; Lederman, 2004; McComas, 1996), it is our argument that an additional characteristic of science is an essential tool in teaching evolution in an equitable manner: the *bounded* nature of science. We've described that the bounded nature of science to be a factor caused by the methodological naturalist assumptions of science (that is, because science requires empirical evidence, questions that are outside this frame are outside the boundaries of science). Thus, not all important questions can be answered scientifically (Southerland, 2000).

As science educators, we must remember that not every knowledge claim that we find useful and productive in our lives is actually a scientific knowledge claim. As described by Smith and Scharmann (1999), it is important for students to understand that science as a way of knowing is very helpful in understanding some aspects of their lives, but nearly useless for understanding others. As such, while it may seem that science contradicts or refutes other ways of knowing, this idea privileges a narrow view that science claims to be the ONLY way of knowing the world. Smith and Scharmann (1999) argue that it is valuable for students to recognize that science does not assert that there are no supernatural forces, and it does not refute the existence of God. Instead, one feature of doing science is that one may not invoke supernatural or metaphysical explanations in constructing a scientific explanation. Scientific explanations must rely on logic, observable evidence, and testing.

That is not the same as saying that unobservable, non-physical forces do not exist; rather, in doing science we cannot resort to the power of non-empirical agents. If the metaphysical or supernatural must be used to construct an explanation, then that explanation violates the assumptions of science, and so is considered nonscientific. There is a crucial distinction between the notions of philosophical naturalism and methodological naturalism, the latter being an aspect of a modern approach to science. The fact that an explanation is not scientific does not make it a weak or flawed explanation—it is simply a nonscientific explanation. That same explanation may be useful for a great number of people in constructing understanding of their lives, but the explanation is simply not consistent with science as a way of knowing.

Although the science/nonscience distinction is a centrally important one in a equitable approach to science teaching, it is also important to distinguish between the realms of science, nonscience, and pseudoscience. While little discussion in the science education literature has focused on the issue of how to define pseudoscience, a few authors have addressed this. A robust attempt was made by Martin (1994), who characterized pseudoscience as having two identifiable constructs: surface properties and depth properties. Surface properties are the features which give it the appearance of a science, including the couching in technical language, making claims to empirical evidence, and the contriving of a subculture, including special organizations, journal publications, seminars, etc. Depth properties are the features that reveal its lack of scientific nature, including propositions that are untestable or already considered to be refuted by current evidence, attempts to isolate the proponents of the pseudoscience from the scientific community, prevention of exposure of their ideas to critical tests, and a dogmatic intolerance of competing theories. In a more general sense, we assert that pseudoscience is a knowledge claim that makes attempts to take on the qualities of science in an effort to gain epistemic weight, but one that fails to encapsulate the qualities of science. A nonscientific knowledge claim does not attempt to take on the trappings of science; instead, it is seen as an alternate way of understanding the world that is to be weighed on the merits of its own epistemic framework. A pseudoscientific claim appears to be scientific (e.g., based on empirical evidence, undergoing peer review) but fails to meet those criteria.

Thus, art would be considered nonscientific, as it does not meet the epistemological criteria of science, therefore is not portrayed as a science. Religion, too, would be considered a nonscientific field, as it does not meet the epistemological criteria of science, but typically is not portrayed as a science. Something like intelligent design, or its intellectual grandparent, creation science, would be considered a pseudoscience. This is because even though they have religious ties (less overtly in the former), these constructs are often portrayed as a form of science. Likewise, astrology and psychic phenomena warrant the label of pseudoscience. While proponents often use scientific-sounding language, often invoking the gravitational pull of stars on our bodies when born, the claim that this affects the subsequent personal life of the individual is without empirical and theoretical warrant. We argue that an equitable approach to science instruction allows students to identify science, nonscience,

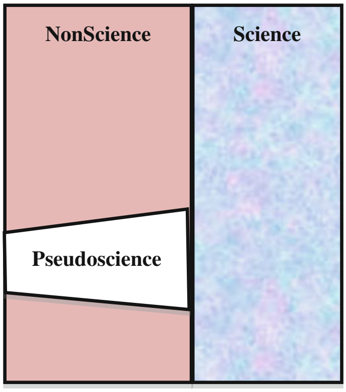

Fig. 4.1 The relation of science, nonscience, and pseudoscience

and pseudoscience, so that they learn to apply the appropriate epistemic criteria for evaluating each in appropriate and useful ways.

As shown in Fig. 4.1, in an equitable approach to the teaching of science, it is important to emphasize to students that not all nonscientific knowledge frameworks are considered as pseudoscience. Instead, many ways of knowing that are central to our lives are not scientific, do not meet the epistemic criteria of science, yet can hold great importance for the individual (e.g., aesthetics, religion, morality, mathematics).

Given the need to teach science to all students as one acknowledges the role of affective issues in shaping learning, helping students recognize the boundaries of scientific knowledge becomes and acknowledging the potential salience of knowledge other than science becomes central to the work of science educators.

In this vein, it would not only be inappropriate philosophically, but ineffective and even irresponsible to be murky or vague in our discussions of pseudoscience. Instead, as we teach, we must keep the “masquerading” facet of our pseudoscience definition in mind as we discuss science, pseudoscience, and other ways of knowing. To lump a religious belief in with astrology or phrenology, if that belief is not portrayed as a scientific finding or assertion, oversteps those boundaries and suggests that the religious belief is inferior to science. For those having experience in the classroom, this “misstep” puts the science teacher in an untenable position—as offending students’ religious sensibilities by suggesting they are inferior to science would negatively influence the affective climate for that student—making meaningful engagement and consideration of the material unlikely. So, lumping religious beliefs in with pseudoscience is not only philosophically questionable (in that one is applying the epistemic criteria of science to evaluate something outside the boundaries of science), but also pedagogically clueless. Lumping religious beliefs in with pseudoscience (when these beliefs do not attempt to enter the masquerade) could be considered irresponsible if in light of science educators’ responsibility to help all students move toward scientific literacy.

Instructional Implications

We have argued here, and elsewhere, that an important aspect of the nature of science is a recognition of the particular strengths and boundaries of science (Settlage & Southerland, 2007). When teaching nonmainstream students, one of the goals of an equitable approach to science is to make the rules explicit for scientific thought, and how those rules are different from our everyday ways of thinking. Thus, in an equitable approach to the teaching of science, we must work to allow students to recognize the limitation of a "scientistic" approach to science teaching. *Scientism* recognizes science as the only legitimate, intellectual approach to constructing useful knowledge. An example of this approach can be found in Mahner's and Bunge's (1996) discussion of the intersection of science and religion. This scientistic approach—the reliance on science as final authority for all truth statements—fails to set limits on the authority of science (Duschl, 1988; Nanda, 1996), as described by Poole (1996):

> The scientific study of a work of art, say a picture, may give an exhaustive account of the chemical constitution of the pigments, the wavelengths of the light they reflect, their reflection factors, masses, and physical distributions. But such a scientific account has hardly begun to say much of interest to the viewer or to the artist. Aesthetic considerations, issues of meaning, and matters of purpose are of far greater importance. A sociological study of the influences on artists' work will have similar limitations. It is not that pictures cannot be described in terms of chemicals, or mental activities in terms of brain functions—they can. What is wrong to assert (for it cannot be demonstrated) is that these scientific accounts are the only valid ones there are—the mistake of ontological reductionism or "nothing buttery" (p. 165).

In Poole's terms, ontological reductionism inherent in scientism denies the importance of other systems of thought, such as art, literature, music, and spirituality/religion, and in doing so, this approach denies much of what is fundamental to individuals in all cultures (Woolnough, 1996). Additionally, some research has concluded that attention to pseudoscience within the science classroom may be fruitful in that it provides an unusual and engaging context for students to examine NOS-related issues (Golden, 2000).

Concluding Thoughts

As students learn the characteristics of science and scientific methodology, they learn the boundaries of scientific knowledge: they learn to identify questions modern science can answer and what questions science cannot. Only when students *begin* to understand the boundaries of science can they recognize the practical and pedagogical limitations of scientism. Perhaps it is on this issue that our position differs subtly from that of Smith and Scharmann (1999). We have not found having students indentify the differences between scientific and other ways of knowing difficult; that is, because it is prefaced by an explicit analysis of the bounded nature of science.

We argue that students need to recognize that (a) there are questions that, because of the methodological naturalism of modern science, science is ill-suited to answer, (b) there are aspects of our lives that would be better served by using other ways of knowing (e.g., art, religion, personal relationships), and (c) because of this, one must apply the epistemic criteria of science only to knowledge said to have been produced in that framework.

We suggest that the broad, over-application of these epistemic criteria to knowledge claims generated outside of science (as is the case with scientism) not only is philosophically flawed, it represents a fundamental pedagogical misstep. If ways of knowing dear to the learner are evaluated using the guideposts of science and found wanting, as has been described previously, it will be difficult to engage that learner in further consideration of science, its processes, or the knowledge it produces. We suggest that a fundamentally important aspect of an effective equitable approach to science teaching includes allowing students to recognize what questions science can answer and what questions it cannot. Consideration of pseudosciences can allow students to better understand the characteristics of science, but science educators must be careful in what they characterize as a pseudoscience and when they apply the epistemic criteria of science. It has long been recognized that scientism is a dangerous force in a classroom. Because of this, it is important to allow students to see that not all useful knowledge is generated by science and that all knowledge claims are not to be evaluated scientifically. That said, recognizing what the assumptions and methods of science are is itself a vital component of scientific literacy. We contend that in the often controversial world of the modern science classroom, the bounded nature of science provides the teacher with a fruitful tool with which to help his/her students negotiate the intersection of science and their everyday ways of knowing—something that can minimize the potential for alienating such students from the world of science.

Teaching the culturally bounded nature of science offers opportunities for nonmainstream students to cross their personal, cultural borders and access the mainstream culture of science. Hodson (2009) eloquently articulates the necessity for a scientifically literate, multicultural public in the following passage with which we close this chapter:

> In short, why does it matter what image of science is presented and assimilated [in schools]? It matters insofar as it influences career choice, and so may have long-term consequences for individuals. It matters if the curriculum image of science is such that it dissuades creative, non-conformist and politically conscious individuals from choosing to pursue science at an advanced level. It matters if the image of science is such that it dissuades women, members of visual minority groups and students from lower socioeconomic status homes from emerging science-related careers or seeking access to higher education in science and engineering because they do not see themselves included and represented in the science curriculum. It matters if our politicians, public servants and industrialists are so ignorant of scientific and technological issues that their decision-making is ill-informed and uncritical. . .Failing to provide every student with an adequate understanding of the nature of science runs counter to the demand for an educative citizenry capable of responsible and active participation in a democratic society. (Hodson, 2009, pp. 142–143)

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Chapter 5
Why the Study of Pseudoscience Should Be Included in Nature of Science Studies

Ronald Good

Background

This chapter is based on a symposium *Pseudoscience in Society and Classroom* held at the June 24–28, 2009, meeting of the International History and Philosophy of Science Teaching Group at Notre Dame University, South Bend, Indiana. It followed a similar symposium *Should Pseudoscience Studies Become an Integral Part of NOS and Scientific Inquiry Curricula?* held at the April, 17–20, 2009, meeting of the National Association for Research in Science Teaching, Garden Grove, California. These symposia, this chapter, and a forthcoming special issue of *Science & Education*, co-edited by Peter Slezak and myself, all focus on how and why the study of pseudoscience should become an integral part of science education.

Rationale

Why should room be made in the science curriculum for the study of pseudoscience? As students learn about science and how it is done, don't they become proficient at recognizing and rejecting pseudosciences like subluxation chiropractic and intelligent design (ID)? The short answer to the latter question is no. Students as well as other citizens are about as likely to be fooled by pseudosciences today as they were decades ago, before the launch of the Russian satellite Sputnik and the many efforts in the United States to improve science education. Part of the answer to the persistent success of pseudoscience in modern societies might be better marketing of products. From about the time Sputnik was launched in 1957 until now, television has made it possible to market just about anything that doesn't actually do physical harm to people.

Another answer to the question of why people are so likely to embrace pseudosciences such as chiropractic and intelligent design (ID) has to do with the nature of

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beliefs and how they develop, in other words the psychology of belief. Children tend to believe what parents and other authority figures tell them, but as they grow older their ability to think more critically usually grows as well and they begin to question authority. One way to assert authority is to invoke science to support claims and getting people to believe a claim is easier if science, or what seems to be science, is used to support the claim. Sorting out real science from pseudoscience is often not an easy task, as seen by the widespread belief in chiropractic, ID, parapsychology, weight loss schemes, easy cancer cures, and countless other products that use the veil of science to change people into believers and consumers. Getting people to believe enough in a product to use it is the goal of all pseudosciences, and today's marketing techniques are more effective than ever in selling the product, whether it is health-related or not.

Going back to our initial question (Why should room be made in the science curriculum for the study of pseudoscience?) we need to reach agreement that science literacy should include the ability to recognize pseudoscience. When *Science for All Americans* was published in 1989, the concept of *scientific habits of mind* was made an integral part of science literacy. Habits of mind like questioning authority, skepticism, curiosity, keeping an open mind, and respecting evidence became central features of the scientifically literate citizen. Being able to recognize bogus claims that promise simple solutions to complex problems was made part of the overall effort to define science literacy. In other words, being able to recognize pseudoscience in its many guises is an important part of what it means to be scientifically literate. More than for other science education reform efforts, *Science for All Americans* (Project 2061, AAAS, 1989) stressed the importance of recognizing pseudoscience as an integral part of science literacy. We return to the question of why pseudoscience should be included in the school science curriculum later in this paper, but now I want to consider how it might be done.

Studying the Nature of Science (NOS)

Identifying general characteristics of the nature of science through study of history and philosophy of science is one path taken by teachers of science who want their students to know something of the nature of science. *Science for All Americans* begins with a chapter on the nature of science, and many characteristics of scientific beliefs and attitudes are identified, including:

1. The world is understandable;
2. Nature's basic laws are the same everywhere;
3. Scientific ideas are subject to change;
4. Most scientific knowledge is durable;
5. The use of evidence is pervasive throughout the various sciences;
6. There is no fixed set of steps that scientists always follow;
7. Hypotheses that cannot be tested are not likely to be useful;

8. Personal biases due to cultural and individual differences should not be part of scientific theories;
9. Evidence rather than authority/power is given preference;
10. Science is open rather than closed.

Many more general characteristics of science can be identified but these are representative of what can be found in *Science for All Americans* and many other sources that describe the nature of science. In addition to learning fundamental concepts of biology and chemistry and physics and other natural sciences, students today are also expected to understand scientific beliefs and attitudes similar to the 10 listed above, summarized as nature of science (NOS) characteristics. When these NOS characteristics are understood by students, it is assumed that they will be able to recognize and (hopefully) reject pseudoscience claims when encountered in their daily lives. However, there is very little evidence that the study of the nature of science automatically translates into greater tendency to recognize and reject pseudoscientific claims that citizens encounter regularly. In order to accomplish this goal it seems reasonable to assume that students need opportunities, as they study science, to analyze at least a few examples of pseudoscience as well. This topic is the focus of the next section.

Studying the Nature of Pseudoscience (NOPS)

Whether the acronym NOPS will become as recognizable as NOS has become in recent years is uncertain, but for now I'll use both as shortcuts when referring to nature of science (NOS) and nature of pseudoscience (NOPS). When studying things, it is often useful to have counter-examples as well as positive examples to be studied. Being able to analyze and understand why a pseudoscience like astrology is not science can be seen as a way of assessing students' understanding of NOS. Rather than simply saying to students that astrology or alchemy or parapsychology or ID or chiropractic and so on are not science and therefore have no place in a science class, the teacher should encourage students to analyze why something like astrology and ID are considered to be pseudoscience rather than science. Some pseudosciences like astrology and phrenology used to be embraced much more strongly than they are today. Studying the positions of stars or the bumps on one's head to determine how to live one's life are taken less seriously today by most people in countries such as the United States, where education is widespread. However, other pseudosciences such as ID and chiropractic continue to enjoy widespread popularity among citizens in the United States. The strength of belief in a particular pseudoscience depends on many factors and these differences among pseudosciences should be better understood.

Chiropractic and ID Compared

Many kinds of pseudoscience could be selected to be studied here but subluxation chiropractic and ID are selected because they are currently widespread and they can have important negative consequences. At first glance it seems that ID and chiropractic have little in common. Chiropractic deals with the body (spine) and ID with the mind. However, a brief look at the history of each pseudoscience is enough to show that they share a very important feature. Since 2005 when Judge John E. Jones III wrote his opinion in *Kitzmiller et al. v. Dover Area School District*, it should be clear to all that ID is simply creationism by a different name. The story surrounding that court case is told nicely by Edward Humes in his 2007 book *Monkey Girl: Evolution, Education, and the Battle for America's Soul*. Creationism is the belief that the Book of Genesis in the Christian Bible is true, a belief common throughout the United States, but especially in southern states. After the publication of Charles Darwin's *Origin of Species* book in 1859 creationism has lost considerable ground among educated citizens in many countries, but in the United States tens of millions of believers continue to hold the belief that their God created everything and is especially interested in people and what they do. An excellent history of the creationist movement in the United States is historian Ronald Numbers' *The Creationists: The Evolution of Scientific Creationism* (1993). Belief in the mystical world of unseen forces is the key link between ID and subluxation chiropractic. Understanding the history of something usually provides important insights about the nature of what is being studied and a good source for chiropractic is *Spin Doctors: The Chiropractic Industry Under Examination* (2002) by investigative reporters Paul Benedetti and Wayne MacPhail. Also, in the case of chiropractic, understanding how political forces rather than scientific data can be used to impose pseudoscience on society is important, as a recent article by Jann Bellamy (2010), the U.S. attorney and President of Campaign for Science-Based Healthcare, in *Royal Pharmaceutical Society of Great Britain* points out (see "Legislative alchemy: the US state chiropractic practice acts").

Subluxation chiropractic was invented by magnetic healer and mystic, D. D. Palmer. He opened his drugless infirmary in Davenport, Iowa, and in 1895 Palmer invented the idea that "subluxations" or blockages in the spine are the cause of many diseases and disabilities. Similar to Andrew Still's earlier ideas about osteopathy, Palmer marketed his subluxation therapy and with the help of his son B.J. was successful in convincing people they could be cured of pain and suffering by submitting to a few quick spinal adjustments to relieve their subluxations. All efforts to locate and test for the existence of the mysterious "subluxation" have been unsuccessful, from the Palmers' time to the present. Like gods and goddesses past and present, nobody has been able to verify the existence of subluxations.

Belief in unseen forces is common and not limited to ID and chiropractic. Religious belief is the most common and most powerful of these beliefs and much has been written about the history and nature of religious belief. Karen Armstrong's (1993) book *A History of God: The 4,000-Year Quest of Judaism, Christianity, and Islam* provides a good look at the wide variety of religious beliefs over the centuries that people invent to satisfy their various needs. More recent critiques of belief in supernatural worlds (e.g., Dawkins, 1998, 2004, 2006; Edis, 2008; Stenger, 2007) and the turmoil in the world of Islam (Edis, 2007) have placed religious belief onto front pages of newspapers and at the top of book bestseller lists. If people are so willing to believe in unseen gods and goddesses, past and present, it is not difficult to see that subluxations and related imaginary forces can be marketed as well. Convincing people to believe in unseen forces is apparently not very difficult.

In my 2005 book *Scientific and Religious Habits of Mind: Irreconcilable Tensions in the Curriculum* I compared these two powerful forces in society and concluded they are not just different, but are basically incompatible. Scientific habits of mind, like the 10 listed earlier in this chapter, are not easy to achieve. However, religious habits of mind like accepting authority, valuing personal testimony over solid evidence, and believing in miracles and life after death seem to be easily accommodated by children and most adults. Pseudosciences like astrology and phrenology and parapsychology and subluxation chiropractic seem to share the "easy-to-believe" characteristic with ID and other religious beliefs. These easy-to-believe traits of pseudoscience and religion are "natural" when compared to "unnatural" ideas in science that require "uncommon" sense. The title to the insightful and highly enjoyable little book by British scientist Lewis Wolpert reflects this natural—unnatural dichotomy: *The Unnatural Nature of Science: Why Science Does Not Make Common Sense* (1992). Coming to understand and believe the many "unnatural" ideas in science is not an easy task for most people, as teachers of science recognize as they learn more of students' pre-scientific conceptions, often called misconceptions. When existing belief systems are strong and they conflict with science in a person's education, it is often science that loses the struggle.

In his book *Religion Explained: The Evolutionary Origins of Religious Thought* (2001), anthropologist Pascal Boyer observes that "...most religions routinely flout the requirement of consistency" (p. 300). He explains that humans have many cognitive processes such as false consensus effect, memory illusions, confirmation bias, and cognitive dissonance reduction that lead us away from evidence-based beliefs. Overcoming these cognitive tendencies is not easy, helping to explain why pseudosciences like ID and chiropractic are successfully marketed by people trying to make money or acquire power over others. The use of reason and evidence in an open, inquiry-oriented environment are required for scientific thought to flourish, overcoming natural cognitive tendencies like confirmation bias.

Avoiding Controversy

Doing the right thing often involves taking a risk. High school biology teachers are very aware of this when they teach evolution in a community where many parents believe in creationism and make it known they disagree with the teaching of evolution. When the science teachers and a few parents in the Dover, PA school system decided ID should not be forced into the science curriculum by the school board, they took a risk by going to court to stop it from happening. When scientists and other faculty at Florida State University fought against politicians, chiropractors, and top-level FSU administrators to prevent the establishment of a graduate school of chiropractic at FSU in 2005, they were taking a risk. In both cases doing the right thing, in terms of science and education, meant opposing the pseudosciences of ID and chiropractic. Controversy could have been avoided if the Dover science teachers and the FSU science faculty had simply allowed the power structures to have their way. Fortunately, they did not and today there is no school of chiropractic at FSU and ID is not part of the science curriculum in Dover, PA schools.

Taking on the issue of pseudoscience, especially if it looks like religious belief may become part of the equation, is a risky business. To question strongly held beliefs of the majority, or even a vocal, powerful minority, is a risky business and most people prefer to avoid controversy simply by staying silent. I chose to use ID and chiropractic as examples of pseudoscience in this chapter because they are strongly held beliefs by many people in the United States. The pragmatic, politically correct position on the relationship between science and religion is that they are not incompatible and most professional organizations in science and education take that position and controversy is largely avoided. The position on the relationship between science-based medicine and chiropractic is more complex, but professional societies like the American Medical Association seem reluctant to speak out and call chiropractic a pseudoscience, even though most physicians would probably like to do so. Some physicians are willing to speak out and warn the public of the dangers of upper-neck manipulations (see website < neck911usa.com > and related video) and scientists who look into chiropractic recognize its pseudoscientific nature.

I have argued earlier in this chapter that a lack of credible evidence is a unifying feature of ID and chiropractic, as it is for other pseudosciences, so the ability to learn that claims lack credible evidence is clearly a crucial factor in recognizing pseudoscience. This is the topic of the next section.

The Role of Placebos in Pseudoscience

Deciding what is or is not credible evidence can involve many factors, including the role of placebos. Especially in medical science, the placebo effect must be controlled for by designing studies so that neither patients nor researchers know who is receiving the experimental treatment. The double-blind study is the gold standard in medical research. In non-medical research that seeks to compare an experimental treatment with a control treatment, the same kind of effort to control personal bias should be used but often is not. Research into the placebo effect has shown that believing in the effectiveness of a medical treatment, for example, can actually cause a physiological response such as reduction of pain for a short period of time. Where one's sense of well-being is involved, the placebo effect can be a complicating factor that must be accounted for in research design.

Controlling for personal or cultural bias is critical in scientific research and is especially difficult to do where people are the research target. It was mentioned earlier that people have many cognitive biases such as false consensus effect, memory illusions, confirmation bias, and cognitive dissonance reduction that can contribute to faulty reasoning. People marketing a particular pseudoscience often take advantage of one or more of these biases to convince people to believe in the effectiveness or "truth" of their product and the placebo effect does the rest. Believing that a chiropractor is realigning one's spine when pushing and twisting one's vertebrae can cause the patient to experience small, short-term relief from pain. However, studies show (Google "chiropractic skeptic" for many sources and read *Spin Doctors* (2002) by Benedetti & MacPhail) that a good massage or a sugar pill or some other placebo "treatment" can cause just as much relief from pain as the more dangerous and costly chiropractic treatment. Believing in something like chiropractic or acupuncture really can help relieve pain to a small degree and for a short period of time, but many related claims of medical cures by these pseudosciences are bogus. By now it should be clear that belief and its resulting placebo effect can be a very important tool in the pseudoscience toolkit, especially where pain relief is involved. The history of belief in many pseudosciences shows how important the placebo effect was and continues to be in gaining followers and true believers.

The Importance of Content Knowledge

Another important factor in the study of pseudoscience is the role of the science content knowledge of the particular thing being studied. Staying with our examples of ID and chiropractic, making informed decisions about either one requires a fair amount of knowledge of the history and nature of each. For ID, where claims might involve biochemistry of the cell or age of the Earth and life on Earth or the relatedness of humans and chimpanzees, knowledge of the relevant sciences can be very helpful in showing that the claims of the ID proponents are made without a valid scientific basis. Also, a knowledge of the history of ID and its relationship to the earlier "creation science" and that both are basically creationism dressed up in science-sounding terms help place ID in proper perspective. Evolutionary biologist Jerry Coyne (2009a, 2009b) provides an eminently readable account (*Why Evolution Is True*) of evolutionary theory that shows why ID fails all scientific tests. For chiropractic, where claims revolve around the mysterious "subluxation" and the importance of spinal manipulation in relieving pain and fighting other disabilities and diseases, knowledge of human anatomy and physiology can be very helpful in showing that claims are bogus. Also, knowing that chiropractic originated in the mind of a mystic former grocer who was into magnetic healing helps place it in proper perspective. In short, there is no good substitute for scientific and historical knowledge when pseudoscience claims impinge on a domain of science like biology or physics or medical science. This, of course, is true for science education as well. We can teach well only what we know well and having a sound knowledge of the basics of one's field, including its history, is an important tool in the science education toolbox.

Conclusions and Implications for Science Education

The study of pseudoscience should become an integral part of nature of science (NOS) study in the school science curriculum for a number of reasons. *First*, belief in pseudoscience continues to be a widespread problem in the twenty-first century even though science has been a dominant force in the United States and other countries for well over 50 years. People seem to fall victim to a wide variety of pseudosciences just about as easily now as before the time science education became a priority after Sputnik was launched in 1957. *Second*, having pseudoscientific examples such as ID and chiropractic to study along with positive examples of science should help students better understand the nature of science (NOS) as well as the nature of pseudoscience (NOPS). Rather than simply dismissing questions surrounding ID for example, as not science, the science teacher should help students understand what it is about ID that makes it pseudoscientific. *Third*, studying NOPS as a part of studying NOS should help students think more about their own beliefs and how they develop. An important part of the process of changing one's beliefs is realizing the inadequacy of one's current state of knowledge, whether in science or in other fields.

Linking religious belief to pseudoscientific belief is likely to cause some people to question why I chose to do so, and they deserve an answer. It was mentioned earlier that philosopher Daniel Dennett (2006) (*Breaking the Spell*), myself (*Scientific and Religious Habits of Mind*), and others have proposed that religion, like other important forces in society, be investigated using all scientific means available. The claim that science and religion are separate domains and should not or cannot be mixed is simply not valid from a scientific perspective. Not only is it important to know how early religious training affects later efforts to help students become scientifically literate, it is reasonable to assert that science can tell us something about the nature of religious belief itself. The religious "impulse" or "instinct," as some call it, has been studied recently by neuroscientists and others, and it is becoming increasingly clear that religious belief, like other universal human traits, is a function of brain behavior. Science can test supernatural worldviews (see Fishman, 2009) and more researchers are doing so (e.g., see Wade *The Faith Instinct*, Pascal Boyer *Religion Explained*, 2009, and Andrew Newberg, E. D'Aquili, and V. Rause, *Why God Won't Go Away*, 2001). Brain science has brought the supernatural (religious belief) into the natural world that can be tested, and as that happens it seems that certain pseudoscientific and religious habits of mind have much in common. Having faith in something without critical analysis is common to both religion and pseudoscience even though the origins or causes may differ.

The open nature of science is such that absolute claims cannot be used. Given the nature of the evidence for or against a particular claim or hypothesis, science can assign a high or low probability but it cannot be 0 or 1. Bayesian theory in probability corresponds to this requirement in science by assigning a likelihood that something is true. All of us who have studied science and done research know this and yet many have difficulty applying this reasoning to the supernatural, especially where strongly held religious beliefs are concerned. As Daniel Dennett has observed, belief in belief is strong in the United States. However, when the evidence for or against a claim is made available for all to see, an estimate of the likelihood of it being true can be produced. Of course the problem is that where pseudoscience and religion are concerned, rationality is not a central feature or requirement. To help break the spell of belief in belief wherever it is found, those committed to increasing science literacy must realize that religious belief, like many kinds of pseudoscience belief, can contribute to irrational, unscientific habits of mind.

How the study of pseudoscience might be made an integral part of nature of science studies is a question that requires careful thinking and research, and teachers of science in our schools will be important participants in the effort. The approach implied by the arguments in this chapter is not embraced by some who might agree that the study of pseudoscience should become part of NOS studies. Using controversy to challenge beliefs is an approach some people find uncomfortable. For example, in evolution education some teachers try to avoid human evolution while otherwise doing a pretty good job in helping students see the central importance of modern Darwinian evolution in biology. Pseudoscience study does not have to include an emphasis on relatedness to religion if the teacher, for one reason or another, does not want to include that. I have included the relatedness issue in this chapter because I think it is important and I feel comfortable doing so. For too long, "belief in belief" has restricted the kinds of discussions and research in science education that should be part of the overall effort to improve science literacy. Recently I asked a colleague for examples of questions that he said in a published paper could not and probably should not be asked by science. After waiting many weeks the answer has not yet arrived.

Willingness and ability to critically analyze one's beliefs regarding pseudosciences like ID and chiropractic and astrology and parapsychology and acupuncture and magnetic healing and so on should be an important part of science literacy. To what extent are one's beliefs grounded in reason and credible evidence and to what extent are they grounded in acceptance of authority or peer pressure? The scientifically literate person should not only be *able* to answer that question, she should *want* to answer it as well.

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Chapter 6
The Status of the Nature of Science in Science Education in Lebanon

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In response to social pressures, the past three decades have seen calls for a change of emphasis in science education from a focus on academic scientific education, which caters for the needs of a minority of students interested in pursuing careers in scientific fields, to giving prominence to preparing scientifically literate citizens who are capable of taking informed decisions regarding science-related issues; citizens who are capable of using science productively in their lives (see for example American Association for the Advancement of Science [AAAS], 1989; Millar & Osborne, 1998; National Research Council [NRC], 1996; Osborne & Dillon, 2008). The calls for preparing scientifically literate citizens have been echoed in the Lebanese curriculum (BouJaoude, 2002), which was developed between 1996 and 1999 and which is still being used until the present.

Emphasis on preparing scientifically literate individuals requires that a curriculum include more than facts, concepts, principles, laws, hypotheses, theories, and models of science. In addition to these, the curriculum should emphasize the investigative nature of science (using methods and processes of science), science as a way of knowing (accentuating thinking, reasoning, and reflection in the construction of scientific knowledge and the work of scientists, the empirical nature of science, ensuring objectivity of science, use of assumptions in science, relationship between evidence and proof . . .), and the interaction of science, technology, and society. In this respect, science teaching should go beyond helping students solve algorithmic end-of-chapter textbook problems to tackling relevant and contextual everyday problems (Anderson, 1987; National Research Council [NRC], 1996; National Science Teachers Association [NSTA], 1993; Osborne & Dillon, 2008; Yager, 1989, 1991).

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Highlighting the investigative nature of science and science as a way of knowing suggests that a curriculum is giving some prominence to helping students understand the nature of science (NOS). Specifically, emphasizing "science as way of knowing" relates to questions about the production of scientific knowledge as well as the characteristics of this knowledge; that is issues related to NOS. In other words, including NOS in the curriculum is important for promoting scientific literacy. Lederman (1999) argues that an appropriate understanding of NOS enables the public to make more informed decisions regarding science-related issues. Likewise, the development of scientific literacy is supported by scientists for the purpose of ensuring public and political support for scientific activities.

In addition to its potential in promoting scientific literacy, NOS is useful in science education for another purpose. It is believed that a learner's science worldview provides a framework that is used to interpret and make sense of science-learning experiences (Cobern, 1996; Edmondson, 1989; Songer & Linn, 1991). Such worldview is related to students' conceptions of NOS because students' science worldviews include what scientific knowledge is and how it is produced. Designing curricula and implementing instructional practices based on NOS are important in helping students internalize more authentic worldviews of science in order to make more sense of science learning. Therefore, teaching NOS provides an understanding and appreciation of how scientific knowledge is constructed. This authentic view of science leads to meaningful learning, better understanding of science content, and awareness of scientific research (Lederman, 1992).

It is not surprising then to find many science educators and major science and science education organizations that have advocated the development of an appropriate understanding of NOS by students and teachers alike. These educators and organizations have asserted that understanding NOS is a central characteristic of a scientifically literate individual (American Association for the Advancement of Science, 1989; Lederman, 1992). According to these organizations and to science educators, understanding NOS involves helping students understand science and the scientific method as they actually occur rather than as they are expected and thought to happen by theoreticians. This understanding may help students understand science better, and may make science more accessible to students at all age levels.

NOS objective have existed in science curricula since the 1900s (Abd-El-Khalick, Bell, & Lederman, 1998; Lederman, 1992). At that time, NOS objective emphasized teaching the scientific method because of the dominance of logical positivism which assumed that scientific theories were formulated through the use of the scientific method. However, the study of the history of science showed that the rigid form of science promoted by logical positivists did not exist in history. Science does not progress by the accumulation of facts and theories only, but also by the development and change of theories. As a result, NOS objectives focused on science processes and inquiry during the 1960s (Lederman, 1992) to make students aware of uncertainties and doubts that face scientists during investigations. Currently, the NOS objective is included as a critical component of scientific literacy, and views of NOS are based on well-established aspects that refer to the epistemological commitments underlying science activities. Science is considered to be tentative or subject to change given the fact that scientific theories change in the light of new evidence. In addition, science is empirical or based on observations of the natural world. However, what makes science tentative is the fact that science is also the product of human inference, imagination, and creativity and is theory-laden. Therefore, theory-laden science adds a subjective component to NOS because a scientist's theoretical background, personal beliefs, experiences, and expectations play a role in determining the problem to be investigated, the methods to be used, as well as the data to be collected and interpreted, which requires creativity and imagination. Finally, science is culturally and socially embedded. Scientists cannot work in isolation; they need the collaboration of the scientific community and are affected by the culture.

Despite the endurance of NOS objective, research shows that students do not have an adequate understanding of contemporary views of NOS (Abd-El-Khalick et al., 1998; Lederman, 1992). This might mean that science teachers have not, as of yet, attempted to translate NOS into classroom practices. First, it could be that science teachers themselves lack adequate understanding of NOS (Abd-El-Khalick et al., 1998; Lederman, 1992). Other constraining factors on teachers are classroom management concerns, pressure to cover content, teaching experience, and concerns for student abilities (Abd-El-Khalick et al., 1998). Both the importance of NOS as well as the lack of adequate student understanding of NOS, have paved way for an active area of NOS research in science education worldwide. The same can be said about NOS research in Lebanon.

Purpose

The purpose of this chapter is to describe the status of NOS in science education in Lebanon. Specifically, the chapter answers the following questions:

1. How is NOS represented in the Lebanese science curriculum?
2. How is NOS represented in Lebanese science textbooks?
3. What are Lebanese students' and teachers' conceptions of NOS?
4. How can students' conceptions of NOS be improved?
5. Is there evidence that NOS is being taught in Lebanese science classrooms?
6. What lessons can be learned from the experience of Lebanon in attempting to incorporate NOS in science education?

Data Sources

Data sources for the study included: (a) published research articles in professional and refereed journals; (b) theses in 4-year programs in universities in Lebanon; (d) refereed proceedings; and (e) chapters in edited and refereed books.

Criteria for including a study included having a clearly delineated research focus and question(s), theoretical framework, methodology, empirical base, results, and discussion sections.

NOS in the Lebanese Curriculum

According to the Center for Educational Research and Development [CERD] (1995), the Lebanese curriculum developed in the late 60s and early 70s and implemented until 1998 was not meeting the demands and requirements of the present society and was not preparing students adequately for the future. CERD (1995, 1997) asserts that the curriculum used until 1998 was outdated in terms of content, lacked general and specific objectives, and was mainly focused on the theoretical rather than the practical aspects of knowledge. A reform plan was crucial for developing an up-to-date curriculum which meets the demands of an ever-expanding and continuously changing world. The 1995 Lebanese Educational Reform Plan and the curriculum that was developed as a result of this plan paid significant attention to science by increasing the number of hours apportioned to science teaching and emphasized hands-on and minds-on science.

In order to find out whether the new Lebanese science curriculum has the potential to prepare scientifically literate citizens, BouJaoude (2002) investigated the balance of scientific literacy topics in the science curriculum. Synthesizing the common aspects of the different definitions of scientific literacy and updating and adapting previous frameworks of scientific literacy, BouJaoude (2002) developed a framework to analyze the new Lebanese science curriculum. This framework consisted of four aspects: The knowledge of science (Aspect 1), the investigative nature of science (Aspect 2), science as a way of knowing (Aspect 3), and interaction among science, technology, and society (Aspect 4). Aspect 1 deals with the facts, concepts, principles, laws, hypotheses, theories, and models of science which should be known by the scientifically literate person; Aspect 2 reflects the use of methods and processes of science such as observation, classification, inferring, recording, and data analysis, and emphasizing thinking in doing science; Aspect 3 focuses on thinking, reasoning, and reflection on how scientific knowledge is produced and how scientists work and finally; Aspect 4 includes the influence of science on society, the inter-relationships among science, technology, and society, and the ability to understand careers and science-related societal issues. In this framework, the investigative nature of science (Aspect 2) and science as a way of knowing (Aspect 3) are related to NOS.

BouJaoude used this framework to analyze and categorize the general objectives, introductions, objectives, instructional objectives, and activities for grades 1, 2, 4, 5, 7, 8, 10, and 11. Two raters carried out the analysis independently to insure reliability. Results showed that the Lebanese science curriculum focused, especially the details at the level of instructional objectives and activities, almost entirely on aspects 1, 2, and 4 of the scientific literacy framework. Aspect 3 was neglected in the detailed curriculum in spite of the fact that it was prominent in the general objectives.

As was mentioned earlier, aspects 2 and 3, namely the investigative nature of science and science as a way of knowing, focused on helping students develop appropriate views of NOS. Thus, although the new Lebanese curriculum emphasized the investigative nature of science, the lack of emphasis on science as a way of knowing is problematic. Aspect 2 is necessary but not sufficient for promoting NOS views. Aspect 2 provides students with opportunities to use methods and processes of science, but it does not necessarily improve NOS views as a by-product of hands-on science if it is not accompanied by minds-on science. On the other hand, aspect 3 can provide students with metacognitive tools to reflect upon science as an enterprise. It helps students internalize NOS views because it provides students with opportunities to reflect on their knowledge and the mental or manual skills they acquire so that they may be able to transfer the knowledge and skills to new situations. As a result, students understand the nature of observations and their relationships to theory, the empirical nature of science, the necessity of striving for objectivity, the use of assumptions, and the role of self-examination in science among other things. It can be concluded that the lack of emphasis on aspect 3 in the Lebanese curriculum does not provide a comprehensive representation of NOS and thus the Lebanese curriculum does not have the potential to help students develop appropriate conceptions of NOS.

NOS in Lebanese Science Textbooks

It is well established that science textbooks play an important role in science teaching because they provide students with the required curricular content and shape the way students and teachers perceive the scientific endeavor. This is true in Lebanon where students depend almost entirely on studying the content of the textbook especially at the two levels, Grades 9 and 12, where there are public exams. If science textbooks present science as a body of knowledge developed through the scientific method, then students will acquire an inadequate understanding of NOS (Chiappetta, Fillman, & Sethna, 1991; Chiappetta, Sethna, & Fillman, 1993). Therefore, one of the important steps in educating scientifically literate students who hold acceptable views of NOS is to use science textbooks that address the four aspects of scientific literacy provided in the framework developed by BouJaoude (2002). Consequently, to find out whether Lebanese science textbooks promote scientific literacy, Harbali (2000) examined 18 science textbooks that comply with the new Lebanese science curriculum. Physics, chemistry, and life science textbooks of Grades 7 and 10 were selected for analysis and a 10% sample of the total pages was randomly selected for analysis by using the scientific literacy framework mentioned above. Two raters carried out the analysis independently to insure reliability. Results showed that the analyzed textbooks relied on science as a body of knowledge and as a way of investigation only, neglecting science as a way of knowing and interactions among science, technology, and society. Due to the absence of aspect 3, it can be concluded that Lebanese science textbooks, similar to the new Lebanese science curriculum, do not have the potential to help students attain informed conceptions of NOS.

Lebanese Students' and Teachers' Conceptions of NOS

A number of NOS studies in Lebanon investigated students' and teachers' conceptions of NOS given the fact that research worldwide has shown that students and teachers do not possess adequate understandings of NOS (e.g., Billeh & Hasan, 1975; Lederman, 1992; Rubba & Anderson, 1978). Research on conceptions of NOS suggests that students believe that scientific knowledge cannot be questioned and that scientists' major aim is to uncover natural truths. Moreover, Lederman (1992) asserts that even science teachers have inadequate understanding of NOS. For example, many teachers do not think that science is tentative. Likewise, Pomeroy (1993) suggests that some scientists and science university professors have traditional Baconian views of NOS, which are transferred, through teaching and evaluation practices, to science teachers who, in their turn, transfer them to their students. The following section summarizes the results of research studies conducted in Lebanon that investigates Lebanese pre-college students', college students', and school teachers conceptions' of NOS.

Pre-college Students' Conceptions of NOS

Abd-El-Khalick and BouJaoude (2003) examined middle-school students' definitions of science and perceptions of its purpose and usage. Participants in this study were 80 Grade 7 and Grade 8 students randomly selected from four schools in Beirut. Students filled out an open-ended questionnaire and participated in follow-up semi-structured interviews that aimed to generate in-depth profiles of their views of the target aspects of NOS. Results indicated that the majority of participants held rather restricted views of science: They defined science as an academic subject that "furnishes information about the world," perceived its purpose as preparation for higher studies and careers, and saw themselves and others using science in academic, rather than everyday life, settings. Additionally, students' conceptions were related to their socioeconomic status and type of school (public vs. private). For example, a higher percentage of students in the public system compared to private schools defined science as a school subject, remarked that they did not use science in their everyday life, and indicated that science is used by others in academic settings. On the other hand, more students in private schools than in public schools believed that the purpose of science is to solve everyday problems.

BouJaoude (1999) assessed secondary school students' beliefs about the sociology and epistemology of science. Participants were 572 Grade 11 and 12 students from 16 schools in which English is the language of instruction. The schools were selected to represent different regions in Lebanon. Participants were administered 15 items from the Views on Science-Technology-Society (VOSTS) questionnaire (Aikenhead, Ryan, & Fleming, 1989) to assess their conceptions of three components: science and technology, social construction of scientific knowledge, and nature of scientific knowledge. VOSTS is an inventory of student viewpoints about science and how science is related to technology and society. Except for their beliefs that science changes and that classification schemes are not copies of reality, most students subscribed to traditional NOS views. The author argued that, similar to university curricula, the Lebanese K-12 science curriculum emphasizes science content to the neglect of explicit goals regarding the epistemology and sociology of science. Such an emphasis results in students at all educational levels possessing strong science content backgrounds but naïve views about NOS.

College Students' Conceptions of NOS

Dagher and BouJaoude (1997) explored how some university biology majors in Beirut, Lebanon, accommodated the theory of biological evolution with their existing religious beliefs. Sixty-two students enrolled in a required senior biology seminar responded to open-ended questions that addressed (a) their understanding of the theory of evolution, (b) their perception of conflict between this theory and religion, and (c) whether the theory of evolution clashed with their own beliefs about the world. Based on their responses, 15 students were selected for an in-depth exploration of their written responses. Students' answers clustered under one of four main positions: for evolution, against evolution, compromise, and neutral. The authors suggested that students are more likely to develop appropriate understandings of evolution if they are taught about the nature of scientific facts, theories, and evidence and are given the opportunity to discuss their values and beliefs in relation to scientific knowledge; topics about which they did not seem to have any knowledge.

In a continuation of the above study, Dagher and BouJaoude (2005) explored how the same college students understand the nature of the theory of evolution and evaluate its scientific status. Semi-structured interviews were conducted with 15 college biology seniors in which they were asked to explain why they thought evolution assumed the status of a scientific theory, how it compared to other scientific theories, and what criteria did they use to determine if an explanation was scientific or not. Students' responses encompassed five themes that included evidence, certainty, experimentation, method of theory generation, and prediction. Those themes focused on the theory's empirical dimension, which seemed to be derived from a generic and simplistic model of physical science theories that valued direct evidence. Demanding that evolutionary theory conform to this model revealed a misunderstanding of NOS. This misunderstanding was expressed in relation to aspects of methodology, explanation, and prediction.

Teachers' Conceptions of NOS

It has long been realized that teachers are the primary intermediaries of the science curriculum (Brown & Clarke, 1960). In what concerns NOS, this means that if teachers do not have adequate understanding of NOS, they cannot convey NOS views to students even if NOS views are properly addressed in the science curriculum and textbooks. Therefore, teachers' conceptions of NOS play a definitive role in the implementation of science curricula, and teachers will tend to faithfully implement science curricula that they perceive as reflecting their own views of NOS (Travis, 1994). Consequently, it was important to elucidate Lebanese teachers' conceptions of NOS in order to prepare more effective preservice and in-service teacher education programs in Lebanon.

Elementary School Teachers

Abd-El-Khalick (2001) assessed the influence of an explicit, reflective activity-based approach, implemented in the context of a science content course, on preservice elementary teachers' views of some aspects of NOS. At the beginning of the course, generic activities were used to explicitly introduce the 30 participants to 6 NOS aspects, which became a theme permeating all following instruction and discussions. Whether participants were engaged in learning science content or inquiry skills, they were prompted to reflect on their experiences from within the target NOS aspects. An open-ended questionnaire in conjunction with individual interviews was used to assess participants' NOS views. Post-instructional responses revealed several desired changes in participants' views. However, several participants abandoned a "scientistic" worldview only to adopt a "naïve relativistic" one. Moreover, participants were not successful in transferring their acquired NOS understandings, which they successfully demonstrated in the context of familiar course content, to less familiar content. The study raised questions regarding the interaction between the context in which preservice teachers learn about NOS and their ability to apply their understandings to novel contexts, and the interaction between learners' epistemic worldview and their learning about specific NOS aspects.

As mentioned earlier, Abd-El-Khalick and BouJaoude (2003) investigated middle-school students' definitions of science and perceptions of its purpose and usage. Science teachers and school administrators of the students who participated in the study were also interviewed regarding their views of the same aspects. Students' views of the target NOS aspects were similar to a large extent to those of their teachers and school principals despite differences in the complexity of the language used to convey these views. The teachers and administrators held equally restricted and naïve views of science as a mere academic discipline and/or a method aimed at collating and documenting "facts" about the natural world, discovering "truths" about the workings of natural phenomena, and/or producing useful inventions that target the enhancement of the human condition.

Secondary School Teachers

Farah (1994) used the Nature of Scientific Knowledge Scale (NSKS) (Rubba & Anderson, 1978) to assess secondary science teachers' understandings of NOS, and explore whether those understandings were related to participants' sex, years of teaching experience, and subject matter taught (chemistry versus physics). Participants were 34 chemistry and physics teachers (41% female) with teaching experiences ranging from 7 to 9 years. They were selected from private and public schools in Beirut and northern Lebanon. Participants' understandings of NOS were unsatisfactory as indicated by low NSKS scores, and not related to the three aforementioned variables.

Similarly, BouJaoude (1999) obtained unsatisfactory results when he assessed secondary school teachers' as well as students' beliefs about the sociology and epistemology of science. Participants were 124 science teachers (78% female) drawn from 16 schools in which English is the language of instruction. The schools were selected to represent different regions in Lebanon. All teachers were university graduates and had an average of 6.3 years of teaching experience. Similar to the students, the participant teachers were administered 15 items from the VOSTS questionnaire to assess their conceptions of three components: science and technology, social construction of scientific knowledge, and nature of scientific knowledge. Students and teachers held remarkably similar conceptions except that more teachers than students thought that teamwork was crucial to conducting science. Moreover, except for their beliefs that science changes and that classification schemes are not copies of reality, most teachers subscribed to traditional NOS views.

Improving Students Conceptions of NOS

Khishfe and Abd-El-Khalick (2002) investigated the influence of an explicit and reflective inquiry-oriented, as compared to an implicit inquiry-oriented, instructional approach on sixth graders' understandings of NOS. The study emphasized the tentative, empirical, inferential, and imaginative and creative aspects of NOS. Participants were 62 Grade 6 students in two intact groups. The intervention or "explicit" group was engaged in inquiry activities that were followed by reflective discussions of the target NOS aspects. The comparison or "implicit" group was engaged in the same inquiry activities. However, these latter activities included no explicit references to, or discussion of, any NOS aspects. Engagement time was balanced for both groups. An open-ended questionnaire in conjunction with semi-structured interviews was used to assess participants' NOS views prior to, and at the conclusion of the intervention, which spanned 2½ months. Prior to the intervention, the majority of participants in both groups held naïve views of the target NOS aspects. They believed that scientific knowledge is certain and does not change. They were unable to see the difference between observation and inference, did not have adequate understanding of the role of evidence in generating knowledge, and noted that scientists do not use imagination and creativity. The views of the implicit group participants were not different at the conclusion of the study. By comparison, substantially more participants in the explicit group articulated more informed views of one or more of the target NOS aspects. Participants who showed informed views of NOS believed that scientific knowledge can change and noted that scientists use inference, evidence, creativity, and imagination to generate scientific knowledge. Thus, an explicit and reflective inquiry-oriented approach was more effective than an implicit inquiry-oriented approach in promoting participants' conceptions of NOS. These results do not support the intuitively appealing assumption that students would automatically learn about NOS through engagement in science-based inquiry activities. Developing informed conceptions of NOS is a cognitive instructional outcome that requires an explicit and reflective instructional approach.

In a similar study, Yacoubian and BouJaoude (2010) investigated the effect of reflective discussions following inquiry-based laboratory activities on Grade 6 Lebanese students' ($n = 38$) views of the tentative, empirical, subjective, and social aspects of NOS. The study used a pre- and post-test control-group design. During each laboratory session, students worked in groups of two. Later, experimental group students answered open-ended questions and then engaged in reflective discussions about NOS. Control group students answered open-ended questions about the content of the laboratory activities then participated in discussions of the results of these activities. Data sources included an open-ended questionnaire used as pre- and post-test, answers to the open-ended questions that experimental group students answered individually during every session, transcribed videotapes of the reflective discussions of the experimental group, and semi-structured interviews. Results indicated that explicit and reflective discussions following inquiry-based laboratory activities enhanced students' views of the target NOS aspects more than implicit inquiry-based instruction. Moreover, implicit inquiry-based instruction did not substantially enhance the students' target NOS views. This study also identified five major challenges that students faced in their attempts to re-conceptualize their NOS views. These were as follows: (1) the challenge of viewing science as a relative enterprise, (2) the challenge of differentiating among different activities done during inquiry, (3) the challenge of seeing the importance of different scientific explanations and their subjective nature, (4) the challenge of viewing scientific experiments as tools rather than goal of science and viewing communication as a tool similar to experimentation in the construction of scientific knowledge, and (5) the challenge of understanding the relation between personal learning of science and construction of scientific knowledge.

Kotob (2006) investigated the effect of using history of science while learning science on students' conceptions of the tentative and empirical nature of scientific knowledge and the role of scientists' creativity in generating scientific knowledge. Participants were 48 Grade 8 students attending a private school, but coming from low SES families. Students were randomly assigned to an experimental and a control group. Both groups were pre- and post-tested for their conceptions of the three target aspects of NOS. The same teacher taught both groups. The experimental group was taught about atomic theory and chemical reactions using a historical approach, while instruction in the case of the control group lacked a historical perspective. The intervention was delivered over the course of 22 class sessions. Results indicated that the experimental group significantly outperformed the control group on the tentativeness subscale; no significant differences were evident in the case of empirical and creative NOS subscales.

Finally, BouJaoude, Sowwan, and Abd-El-Khalick (2005) investigated the effect of using drama as a supporting learning strategy on students' conceptions of NOS. Participants were 32 Grade 10 and 11 students from a private all-girls' school in Beirut. Of the students, 14 participated in a drama activity while the remaining students were considered the control group and were only required to attend the performances. The drama group met for 3 hours one day of the week for 6 weeks to write scripts about the development of the concept of light in the work of four Arab scientists, and then they played the drama piece in front of the control group, other students, and teachers and school administrators. Data sources included open-ended questionnaire about the tentativeness, testability, and the theory-laden and empirical aspects of NOS and the researcher's field notes and reflections. Results showed that students in the drama group articulated more informed views of all four aspects of NOS.

NOS in Lebanese Science Classrooms

The aforementioned studies about teachers' conceptions of NOS led to the conclusion that Lebanese science teachers do not possess appropriate views of NOS. However, research was needed to find out how teachers' views of NOS were or were not translated into their instructional planning and actual practices in science classrooms because it cannot be assumed that teachers' conceptions are necessarily and directly reflected in classroom practice (Bell, Lederman, & Abd-El-Khalick, 2000). In point of fact, research has shown that translation of conceptions into practice is a complex process that is mediated by many factors such as teachers' level of experience and the intentions and perceptions of their students (Lederman, 1999). Consequently, Saad (2008) and Sarieddine (2009) conducted studies to address this issue.

Saad (2008) investigated the relationship between teachers' knowledge and beliefs about inquiry and NOS and their classroom teaching practices in middle- and high-school science classes. The study sample was randomly drawn from the City of Beirut and used a two-stage probability sampling design with schools as the first level sampling units and teachers as the second level units. Schools were classified into private and public, and each was classified into five groups: (1) schools containing elementary and intermediate classes (Elementary / Intermediate), (2) schools containing intermediate and secondary classes (Intermediate / Secondary), (3) schools containing intermediate classes (Intermediate); (4) schools containing secondary classes (Secondary); and (5) schools containing elementary, intermediate, and secondary classes (All Levels). In the first stage of sampling, 21 private and public schools were selected for inclusion in the study and constituted approximately 9% of the total number of schools in Beirut (237) (*CERD,* 2002). Teachers completed a Likert-type questionnaire to determine their belief about the nature of and the teaching of science. Classroom observations were also conducted to examine teachers' classroom practices. Data were used to construct profiles for each of the teachers. Results showed that most teachers have naïve views of NOS and that there was no relationship between teachers' views of NOS and their classroom practices.

Likewise, Sarieddine (2009) investigated the relationship between teachers' conceptions of NOS and their classroom practice. In addition, she sought to determine the factors affecting this relationship. For this purpose, seven high school biology teachers who had completed teaching diplomas in which NOS was covered, were selected to participate in this study. An open-ended questionnaire entitled “Views of the Nature of Science Questionnaire—form C (VNOS-C)” was used to determine the teachers’ conceptions of NOS. Moreover, semi-structured interviews were conducted with the teachers to confirm the results of the questionnaire and investigate the factors that enhance or impede the relationship between teachers’ conceptions and practice. Classroom observations and analyses of the teachers’ lesson plans were also used to examine classroom practices and instructional planning. Results of the questionnaire and the interviews showed that most teachers do not have acceptable views of NOS. Likewise, analysis of lesson plans showed that the teachers did not plan for teaching NOS, and analysis of videotapes showed no explicit reference to NOS in teaching. A direct relationship between possessing appropriate views of NOS and planning for and teaching these views in the classrooms could not be established. In addition, various factors such as condensed curriculum, teachers’ experience, lack of time, and classroom management, seemed to mediate the translation of teachers’ NOS views into practices.

Summary, Discussion, and Recommendations

The purpose of this paper was to describe the status of NOS in Lebanon. Results of the reviewed studies indicate that NOS views do not permeate the new Lebanese science curriculum, are not addressed explicitly in Lebanese science textbooks, and are not emphasized in science classrooms. Moreover, Lebanese students and teachers have inadequate conceptions of NOS. It seems that the fact that the Lebanese science curriculum and textbooks neglected NOS was reflected in all other components of the teaching/learning process. Fortunately, the intervention studies have shown that some instructional approaches such as the explicit and reflective inquiry-oriented approach (Khishfe & Abd-El-Khalick, 2002), reflective discussions following inquiry labs (Yacoubian & BouJaoude, 2010), using the history of science (Kotob, 2006), and the use of drama (BouJaoude et al., 2005) can enhance some of the aspects of NOS.

Results of studies conducted by Abd-El-Khalick and BouJaoude (2003), BouJaoude (1999), Dagher and BouJaoude (1997, 2005), Abd-El-Khalick (2001), and Farah (1994) indicate that Lebanese students and teachers have inadequate conceptions of NOS. These results are akin to research findings worldwide which suggest that students (e.g., Charron, 1991; Griffiths & Barry, 1993; Lederman, 1992; Ryan & Aikenhead, 1992) and teachers (e.g., Gustafson & Rowell, 1995; Koulaidis & Ogborn, 1995) possess naïve conceptions of NOS. More importantly, studies conducted in Lebanon (e.g., Saad, 2008; Sarieddine, 2009) and similar research conducted internationally show that teachers’ views of NOS do not necessarily influence classroom practice (Abd-El-Khalick et al., 1998; Brickhouse, 1990; Lederman, 1999) due to a variety of factors such as teachers’ level of experience, intentions, and perceptions of students, mediate the translation of conceptions of NOS into classroom practice (Lederman, 1999). These findings are in line with the results of Sarieddine’s (2009) study.

To improve students' conceptions of NOS, there is a need to improve teachers' conception, curricula, textbooks, and adopt appropriate teaching methods. First, if Lebanese students are to acquire adequate conceptions of NOS, then NOS should occupy a prominent position in the curriculum at all its levels, not only at the level of general goals and objectives. This prominence should also be reflected in textbooks because they play a significant role in science education in Lebanon.

The above factors are necessary but not sufficient. To engender significant change in the status of NOS in Lebanese schools, public exams—which are very important for students and parents and consequently for teachers and other stakeholders in the educational process—should include questions about NOS. Notably, these questions should be designed to measure students' understanding of NOS and their ability to apply ideas from NOS across subject areas and in addressing everyday and science–technology–society–environment issues, otherwise the fate of NOS will be similar to that of "*the scientific method*" which has become, at least for some students and teachers, a number of words to be memorized and regurgitated in response to low cognitive level questions.

The above will not happen unless NOS gains prominence in science teacher preparation programs which should focus on providing prospective teachers with nature-of-science-pedagogical-content-knowledge (NOS PCK) (Akerson & Volrich, 2006; Hipkins, Barker, & Bolstad, 2005). Thus prospective science teachers can be encouraged to reflect on how to teach NOS by answering reflective questions similar to the following (Loughran, Berry, Mulhall, & Woolnough, 2006; Loughran, Mulhall, & Berry, 2004): What do you intend the students to learn about the idea? Why is it important for students to know this? What else do you know about this idea (that you do not intend students to know yet)? What difficulties/limitations connected with teaching this idea would you expect to encounter? What specific ways of ascertaining students' understanding or confusion around this idea would you use? These questions are meant to help teachers reflect profoundly about NOS and its teaching; an activity comparable in some respects to what Khishfe and Abd-El-Khalick (2002), Yacoubian and BouJaoude (2010), and BouJaoude et al. (2005) did with middle-schools students.

The results of this research have the potential to inform the reform and improvement of science teacher education programs by emphasizing not only the importance of helping preservice teachers acquire contemporary views of NOS, but helping all teachers to develop pedagogical content knowledge specifically focused on teaching NOS. These programs should also help teachers internalize the importance of curricular NOS-related objectives that should be considered during classroom practice. It is believed that when teachers internalize the importance of NOS teaching, they tend to help students develop appropriate conceptions by using instructional approaches specifically targeted to students' needs.

Numerous such teaching approaches have been developed and tested for their effect in promoting more informed views of NOS among students. These approaches can be classified into three categories: historical, implicit, and explicit approaches (Khishfe & Abd-El-Khalick, 2002). The historical approach assumes that teaching the history of science enhances understanding of NOS. On the other hand, using an implicit approach assumes that engaging students in hands-on inquiry-based activities necessarily improves their NOS views, while using an explicit approach is specifically planned to teach the aspects of NOS. The difference between the implicit and explicit approaches is the degree to which students are helped by the teacher to understand aspects of the NOS (Abd-El-Khalick & Lederman, 2000). Research has shown that incorporating history of science does not necessarily enhance students' NOS views (Abd-El-Khalick & Lederman, 2000; Khishfe & Abd-El-Khalick, 2002). It has also shown that the implicit approach is ineffective in promoting NOS views as a by-product of inquiry activities (Khishfe & Abd-El-Khalick, 2002). However, there is evidence to suggest that explicitly addressing specific NOS aspects enhances the effectiveness of using the history of science approach (Abd-El-Khalick & Lederman, 2000). Explicitness, however, is analogous to direct teaching. The intervention studies reviewed above and many other similar studies indicate that explicit teaching should be conducted in an environment in which reflective careful thinking is practiced for it to be effective in teaching and learning NOS.

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Part II
Methodological Advances in the Nature of Science Research

Chapter 7
Teaching and Learning of Nature of Science and Scientific Inquiry: Building Capacity Through Systematic Research-Based Professional Development

Judith S. Lederman, Norman G. Lederman, Byoung Sug Kim, and Eun Kyung Ko

Introduction

Current reform efforts in science education (e.g., American Association for the Advancement of Science [AAAS], 1993; National Research Council [NRC], 1996) have placed renewed emphasis on the importance of students' understandings of science and its processes beyond basic knowledge of scientific concepts. In particular, the *National Science Education Standards* (NRC, 1996) have stated that students should be able to perform authentically scientific inquiry (SI), from problem formulation through communication of results, as well as understand the process and its assumptions. The *Benchmarks for Science Literacy* (AAAS, 1993) does not go as far as advocating that all students should be able to perform a scientific investigation in total, but it does strongly advocate the ability to perform some aspects of inquiry in addition to an in-depth understanding of the nature and assumptions of the process. In addition, both documents consistently support the importance of students' possessing adequate understanding of nature of science (NOS). If there is a difference between the current reform efforts and those of the past, it lies in the emphasis on students' understandings *about* SI in addition to being able to *perform* the process skills associated with inquiry. Students are expected *to know* in addition to being able *to do*.

NOS and SI can be distinguished from the body of knowledge of science to some degree, but ultimately the three aspects of science are intimately related and difficult to separate. SI can be defined as the various processes and strategies that scientists employ to attempt answers to questions of interest (Schwartz & Lederman, 2008). NOS most commonly refers to the characteristics of scientific knowledge that are necessarily derived from how the knowledge is developed (Lederman, 1992, 2007). SI proceeds in certain ways because of the assumptions scientists hold about how we can learn about the natural world, and the processes of inquiry, in turn,

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have significant implications for the ontological status of the knowledge produced. Consequently, it has frequently been argued that students cannot understand the body of knowledge of science in a meaningful way without an adequate understanding of the processes and assumptions inherent to the development of the knowledge (Driver, Leach, Millar, & Scott, 1996; Robinson, 1969; Rutherford, 1964).

For example, students can readily recite a definition for the term "gene," but can they truly understand what a gene is if they are not aware that it is a construct developed by scientists to explain experimental results? The recognition that students should understand NOS and SI is not new; however, advocacy for the inclusion of both in K-12 instruction can be traced back in the literature to at least the turn of the century (Central Association, 1907) and arguably many years prior. Despite the longevity of support for students' understandings of NOS and SI by scientists, science educators, and curriculum reformers, little progress has been made (Lederman, 1992, 2007; McComas, Almazroz, & Clough, 1998; Tobin, Kahle, & Fraser, 1990).

The study providing the focus for this chapter examines the impact of a professional development project called Inquiry, Context, and Nature of Science (ICAN) designed to enhance teachers' and students' understandings of NOS and their ability to perform and understand SI within the context of subject matter concepts stressed by national and state reforms.

Project ICAN provided instructional support for teachers in several critical areas. First, research has consistently indicated that teachers do not experience the development of original or independent scientific investigations in either the science or science education courses comprising their preservice (Gallagher, 1989; Marx et al., 1994) or inservice education. Consequently, science teachers do not typically possess knowledge about SI or the ability to do authentic SI. This project engaged teachers in authentic scientific investigations in collaboration with scientists, followed by in-depth reflections on the nature of the process. This approach provided teachers with the necessary knowledge and skills concerning SI as well as enhanced understandings of foundational scientific concepts, theories, and laws. Second, research has consistently shown that teachers do not possess views of NOS consistent with those advocated in national and state reforms (Lederman, 1992, 2007; Ryan & Aikenhead, 1992). The collaborative efforts of science educators, scientists, and mentor teachers in this project engaged teachers in reflective activities designed to facilitate in-depth understandings of NOS and SI. Third, it is clear that teachers' knowledge about SI and NOS does not automatically translate into classroom practices and instructional activities that promote student learning. Teachers do not generally possess the pedagogical knowledge to transform their knowledge of SI and NOS into productive instruction in either formal or informal settings. Project ICAN engaged teachers in activities aimed at improving their use of an explicit, reflective approach to teaching NOS/SI.

The research questions that guided the project were as follows:

1. What is the impact of Project ICAN on teachers' understandings of NOS/SI?
2. What is the impact of Project ICAN on teachers' pedagogical knowledge of teaching NOS/SI?
3. What is the impact of Project ICAN on students' understandings of NOS/SI?

Background Literature

Improving Teachers' Understandings of NOS

Nature of science (NOS) has been a common theme in science education reform efforts as an essential aspect of scientific literacy (e.g., AAAS, 1993; NRC, 1996). However, students and science teachers do not possess adequate understandings of NOS, irrespective of the instrument used to assess understandings (Lederman, 2007). In light of efforts to improve students' understandings of NOS, recent research has focused on equipping pre- and inservice teachers with an adequate understanding of NOS (e.g., Akerson, Abd-El-Khalick, & Lederman, 2000; Shapiro, 1996).

From a situated learning perspective, learning tied to authentic context (Brown, Collins, & Duguid, 1989; Lave & Wenger, 1991), engaging learners in doing science and historical episodes of scientific knowledge can be meaningful contexts for learning NOS. However, the results from research aimed at enhancing teachers' and students' understandings of NOS have consistently shown that explicit attention to teaching NOS is necessary to improve teachers' and students' understandings of NOS (Akerson et al., 2000). Simply participating in scientific inquiry does not implicitly teach either teachers or students about NOS. Like any other cognitive learning outcome, NOS should be specific and tangible content that teachers intentionally plan to teach and assess in classroom instruction rather than expecting learners to come to know about NOS by just engaging them in doing science or in episodes of history of science (Abd-El-Khalick & Lederman, 2000b). It is imperative to provide learners with NOS-relevant questioning, discussions, and guided reflection to help them understand aspects of NOS. Empirical support has been obtained for the effectiveness of an explicit and reflective approach in enhancing learners' understandings of NOS (e.g., Abd-El-Khalick & Lederman, 2000a; Akerson et al., 2000; Khishfe & Abd-El-Khalick, 2002; Moss, Abrams, & Robb, 2001; Ryder, Leach, & Driver, 1999).

Improving Teachers' Teaching Practice

One assumption that has permeated research on NOS is that teachers' understandings of NOS directly and necessarily impacts their classroom practice. However, results from a series of investigations that directly tested this assumption reveal that this view is too simplistic, relative to the realities of the classroom (Brickhouse, 1989, 1990; Duschl & Wright, 1989; Lederman, 1986; Lederman & Druger, 1985; Lederman & Zeidler, 1987; Zeidler & Lederman, 1989). Teachers' understandings of NOS appears to be essential, but not sufficient, for productrively translating their understandings into science teaching.

Presently, several variables have been show to both mediate and constrain the translation of teachers' understandings of NOS into practice. These variables include pressure to cover content (Abd-El-Khalick, Bell, & Lederman, 1998; Duschl

& Wright, 1989; Hodson, 1993), classroom management and organizational principles (Hodson, 1993; Lantz & Kass, 1987; Lederman, 1995), concerns for student abilities and motivation (Abd-El-Khalick et al., 1998; Brickhouse & Bodner, 1992; Duschl & Wright, 1989; Lederman, 1995), lack of instructional intention to teach NOS (Lederman, 1999; Lederman, Schwartz, Abd-El-Khalick, & Bell, 2001), institutional constraints (Brickhouse & Bodner, 1992), teaching experience (Brickhouse & Bodner, 1992; Lederman, 1995), and lack of subject matter knowledge (Schwartz & Lederman, 2002).

In addition, research on teaching NOS reveals that having teachers exposed to explicit NOS lessons does not necessarily guarantee their own explicit teaching of NOS, even though it helps them improve their understandings of NOS. Specific pedagogical knowledge of NOS instruction should be provided in order to enhance teachers' NOS instruction. In short, teachers' must develop pedagogical content knowledge for NOS just as for any other desired subject matter outcome.

For example, Abd-El-Khalick et al. (1998) investigated the relationship between preservice teachers' understandings and their teaching of NOS. Spanning two semesters, two science methods courses, a microteaching course, and a science field-based internship heavily emphasized NOS and how to teach about NOS. During the following semester, participants completed a full-time student teaching experience. The authors assessed participants' understandings of NOS at the end of the coursework and compared them with their teaching practice in the student teaching internship. The authors found that the participants possessed an adequate understanding of NOS, but few explicitly taught about NOS. Although many participants claimed that they taught NOS, their pedagogical approach to teaching about NOS was simply to involve students in doing science without any attempt to discuss about NOS. They did not recognize their teaching as implicit.

In a follow-up study, (Bell, Lederman, & Abd-El-Khalick, 2000) preservice teachers were taught NOS in a course separate from a course focusing on the pedagogy of NOS. The results indicated that participants were better than those in the prior research study with respect to implementing NOS instruction in an explicit and reflective manner. However, the majority neither included NOS objectives in their lessons nor attempted to assess students' understandings of NOS.

The struggle of implementing explicit NOS instruction was also reported in a study with an inservice teacher (Akerson & Abd-El-Khalick, 2003). It was found that the elementary teacher held informed views of NOS and a strong intent to teach NOS in her lessons. However, her teaching of NOS was initially restricted to implicit approaches of just involving her students in activities of *doing science* without any debriefing for NOS.

The existing literature implies that science educators should specifically help teachers learn how to teach NOS. The efforts should include helping teachers to shift their pedagogical approaches of teaching NOS from implicit to explicit, learn how to assess their students' understandings of NOS, and improve their abilities to integrate NOS into the existing science curriculum. Embracing current research findings, we designed a program called Project Inquiry, Context, and Nature of Science (ICAN) to promote teachers' understandings of NOS/SI and their pedagogical knowledge of how to teach NOS/SI, which ultimately resulted in the improvement of their students' understandings of NOS/SI. We designed Project ICAN as a 5-year professional development program, which continually added teachers each year of the project. Consistent with the well-documented resistance of learners' to change their misconceptions (Wandersee, Mintzes, & Novak, 1994), research studies on improving teachers' understandings of NOS tell us that we should not expect learners to substantially change their conceptions of NOS/SI with only a short duration of learning about NOS/SI (Driver et al., 1996; Khishfe & Abd-El-Khalick, 2002). Thus, it is more unlikely that teachers can learn how to effectively teach aspects of NOS/SI during a professional development program spanning just a couple of weeks.

Program Structure and Activities

Participants

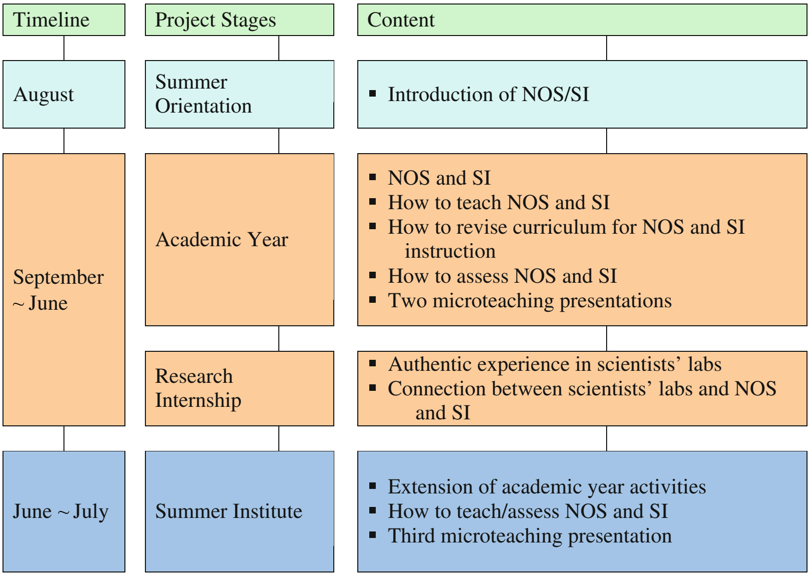
A total of 236 science teachers participated in Project ICAN over the 5 years of the program. Since each teacher taught approximately four classes of approximately 25 students, Project ICAN impacted over 23,000 students. The teachers' group represented six science areas including general science, biology, physics, chemistry, earth science, and environmental science. Almost half of the teacher participants were in elementary schools and the other were in middle schools and high schools. The teachers were diverse in terms of ethnicity and taught in classrooms with highly diverse populations.

Stages of the Project

During each academic year, Project ICAN was comprised of four stages: Summer Orientation; Academic Year; Research Internship; and Summer Institute (Fig. 7.1). During each year of the project, Project ICAN helped the teachers improve their understandings of NOS/SI. In addition, the project addressed pedagogical knowledge of NOS/SI instruction so that the teachers effectively implemented NOS/SI instruction in their classrooms. The following sections describe each stage of the project.

Summer Orientation

Project ICAN began with a 3-day summer orientation in August. During the orientation, the goals of the project and the overview of how the program would proceed were introduced to teachers. The orientation mainly focused on introducing teachers to NOS/SI aspects by engaging teachers in NOS/SI activities. Teachers actively participated in approximately 10 hands-on NOS and/or SI activities (Lederman & Abd-El-Khalick, 1998; National Academy of Science, 1998), such as Tricky Tracks, Real Fossils/Real Science, The Tube, The Cans activities, and Never-ending Labs.



Timeline	Project Stages	Content
August	Summer Orientation	▪ Introduction of NOS/SI
September ~ June	Academic Year	▪ NOS and SI ▪ How to teach NOS and SI ▪ How to revise curriculum for NOS and SI instruction ▪ How to assess NOS and SI ▪ Two microteaching presentations
	Research Internship	▪ Authentic experience in scientists' labs ▪ Connection between scientists' labs and NOS and SI
June ~ July	Summer Institute	▪ Extension of academic year activities ▪ How to teach/assess NOS and SI ▪ Third microteaching presentation

Fig. 7.1 Schematic diagram of the project

In the Tube activity, for example, the teachers were shown a mystery tube and its behaviors. They were then asked to infer what the structure of the inside of the tube looked like and design and construct physical models that behaved in the same way as the original tube. The NOS discussion focused on how and why inferences were different from observations, how human subjectivity led to different models that replicated the original tube in the same way and the inconclusive nature of a scientific model, followed by authentic examples of natural science like models of an atom and the structure of the earth.

In addition to NOS/SI activities, the teachers watched relevant videos that highlighted various aspects of NOS/SI. These videos involved detailed scientific examples as well as conversations with Stephen Jay Gould and Richard Feynman. The teachers also read several NOS/SI-specific articles (e.g., Feynman, 1969). Reflective questions and debriefing discussions followed these various activities to help teachers develop in-depth understandings of NOS/SI. Figure 7.1 provides a summary of the activities of the project as well as a timeline for the calendar year.

Academic Year Activities

Full-day monthly workshops were held from September through July of the following year. Workshops were conducted by the authors, scientists, teachers from previous years of the grant, and other guest speakers. These workshops focused on additional NOS/SI instruction in the context of science subject matter, curriculum revision, and assessment.

September through November, workshops provided teachers with more content-embedded NOS/SI activities in conjunction with debriefing and reflective discussions on aspects of NOS/SI and an explicit approach to teaching about NOS/SI. The activities included the Mystery Bones, Owl Pellet, Disarticulated Skeleton, Pendulum, Hanger, Finger Print, Periodic Table, and Milk activities (see the Project ICAN website, 2010; Lederman & Abd-El-Khalick, 1998). The perspective of the National Science Education Standards on NOS/SI (e.g., NRC, 2000) was specified and the relationship among NOS, SI, and constructivism as an epistemology were discussed to contextualize NOS/SI within the Standards-based lessons. Teachers were encouraged to apply what they learned through ICAN workshops to their classroom, and to bring their classroom experiences to the following ICAN workshop for discussion. Whenever possible, teachers brought videos of their classroom instruction.

During academic years 4 and 5, two-teacher microteaching presentations were planned (in January and May), and one more presentation was arranged for the summer institute (in July). Further description of these microteaching sessions is provided later. In preparation for microteaching presentations, the December monthly workshop provided teachers with model lessons from previous ICAN teachers. One of the model lessons was about the cholera outbreak in London in 1832. Given specific observations described by a doctor in 1832, students were asked for a cause of the cholera outbreak. The lesson was focused on the importance of generating evidence-based explanations and the involvement of human subjectivity in doing science.

After the microteaching sessions in January, subsequent workshops focused on discussing the difficulties that teachers had in teaching NOS/SI and providing additional model lessons to ameliorate the teachers' difficulties. These lessons were followed by discussions about the positive and negative aspects of the lessons.

Teachers were also engaged in activities aimed at integrating technology (e.g., Vernier probes) into NOS/SI instruction. NOS/SI instruction integrated with technology was compared and contrasted with traditional teaching approaches that use technology. Teachers also had the opportunity to evaluate their own curriculum materials relative to the inclusion of aspects of NOS and SI. They chose some topics from their curriculum materials and revised them for NOS/SI instruction with the authors' guidance. Overall, it is was critically important to enable teachers to use what they had learned to revise their curriculum materials as opposed to simply integrated activities provided within the context of Project ICAN.

Internship with Research Scientists

Teachers' lack of knowledge of, and experience with, authentic science processes results in serious limitations to their ability to plan and implement lessons focusing on NOS/SI (Gallagher, 1991; Schwartz, Lederman, & Crawford, 2004). Research findings also support the effectiveness of using an explicit, constructivist-based teaching approach to address NOS and inquiry (e.g., Bianchini & Colburn, 2000;

Khishfe & Abd-El-Khalick, 2002; Roth & Lucas, 1997; Ryder et al., 1999; Smith, Maclin, Houghton, & Hennessey, 2000).

During the academic year of Project ICAN, the teachers participated in a science research internship with practicing scientists on the IIT campus and in surrounding community resources (e.g., zoos, museums). Teachers spent 10 h/week with scientist mentors. The teachers' primary role was as participant observers. They engaged in various aspects of the ongoing investigations in the research settings, discussed specific research content and techniques with the scientists and other researchers, and explored general aspects of NOS/SI. It is important to note that many such internships make the mistake of assuming that teachers can easily transition into the activities of the research team. We tried to avoid this expectation. Research areas included were crystallization, vascular tissue engineering, thermal processing of materials, nutrition, biochemistry, molecular biology, microbiology, protein purification, and genetics. Since explicit and guided attention to and reflection on NOS in the context of the authentic SI is a crucial factor, and considering that scientists are not well versed in making NOS/SI explicit, guided journal writings were assigned for active reflection. Teachers were asked to keep daily journals, guided by focus questions to make connections between their experiences in the research settings with what they were learning about NOS, SI, and unified scientific concepts in the workshop component of the institute. In addition, teachers shared their experiences at the monthly workshops.

Summer Institute (the Second Summer)

During the 2-week summer institute, teachers participated in 10 full-day workshops focusing on NOS, SI, and unifying concepts through a series of explicit activities, readings, and discussions. As reading assignments, for example, teachers read chapters in the book, $E = MC^2$ (Bodanis, 2000) and discussed aspects of NOS and SI embedded in historical episodes in that book. NOS/SI was contextualized within standards-based science subject matter. These sessions targeted a variety of areas including evolution, earth science, physical science, and life science. Research scientists were invited to discuss how scientific theories develop in various areas of science.

In addition to the continued revision of curriculum materials, a strong focus was on the development of performance-based assessments for NOS/SI. It became clear with each passing year of the project that participants benefited from as much time as possible regarding assessment. Teachers simply did not view NOS/SI as they did "traditional" subject matter. Consequently, the myriad of concerns around assessment that teachers always have were further amplified.

Teacher Development Model

One of the enduring, but ancillary outcomes, of Project ICAN has been the development of a teacher development model. Research studies on improving teachers'

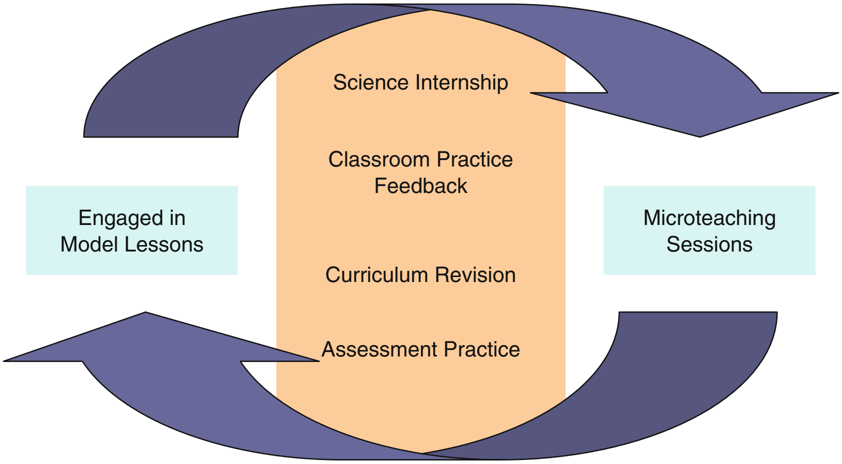


Fig. 7.2 Model of professional development to improve teachers' understandings of NOS/SI and their pedagogical knowledge for NOS/SI instruction

content knowledge and pedagogical knowledge of NOS/SI indicates that teachers should be given opportunities to discuss and reflect on various experiences related to aspects of NOS/SI and teaching about NOS/SI (see the review from Abd-El-Khalick & Lederman, 2000a). Figure 7.2 presents the model of professional development used during Project ICAN to improve teachers' understandings of NOS/SI and their pedagogical knowledge for NOS/SI instruction. Through the four stages of the project (i.e., summer orientation, academic year, research internship, and summer institute), the teachers engaged in various activities. The following section describes each component of this professional development model.

Engaged in Model Lessons

The aim of having the teachers engaged in model lessons integrated with NOS/SI was to help the teachers understand aspects of NOS/SI and to get the teachers to grasp ideas about how to teach NOS/SI. Through the model lessons, Project ICAN promoted an explicit, reflective teaching approach (Abd-El-Khalick & Lederman, 2000a). For example, teachers experienced how the typical mitosis lab (where students simply identify and document the relative frequencies of different stages in onion root tips) can be taught by integrating aspects of NOS and inquiry in an explicit manner (Lederman & Lederman, 2004). Illustrating an implicit approach, the teachers were given a brief review of the different stages of mitosis and how to categorize stages from pictures, and then they were asked to count the number of onion root tip cells in each stage of mitosis within a given field of view under high power. After the counts were entered on a data table, they used the relative frequencies of stages to calculate the relative time required for each stage. In the explicit approach, teachers were given the same brief review, but this time they were asked to describe how they decided when one stage ended and the other began and how scientists determined the demarcation. A striking difference was that the first approach involved the teachers doing an investigation, but without any integration of NOS. Unlike the first one, the second approach engaged teachers in NOS discussions initiated with carefully selected and placed reflective questions, which was followed by discussion of aspects of NOS such as tentativeness, creativity, observation versus inference, subjectivity, and the empirical basis of science.

Microteaching Sessions

It is clear that teachers' knowledge about NOS/SI does not automatically translate into classroom practices and instructional activities that promote student learning about these constructs (Abd-El-Khalick et al., 1998; Duschl & Wright, 1989; Hodson, 1993). Teachers do not generally possess the pedagogical knowledge to transform their knowledge of NOS/SI into productive instruction in either formal or informal settings.

Project ICAN helped teachers understand the difference between an implicit and an explicit approach to teaching NOS/SI through a series of model lessons. In addition, to improve teachers' knowledge of teaching NOS/SI, Project ICAN assigned three microteaching lessons to teachers.

Microteaching refers to peer-teaching practice, in which teachers plan and implement lessons to their peers and receive instructor's and peers' feedback. Although microteaching emerged in the 1960s when teacher educators adopted competence-based education from behavioral psychology (Gage & Winne, 1975), it continues to be a focal point in improving teachers' pedagogical knowledge in most teacher education programs (Gess-Newsome & Lederman, 1990). During Project ICAN, teacher groups of three or four presented three lessons at monthly meetings in January, May, and July. That is, a team of teachers planned and presented a lesson to the rest of their peers. Microteaching was used for two purposes. First, it was a tool of assessing the teachers' pedagogical knowledge of NOS/SI instruction. Second, microteaching assignments were also employed as an intervention, along with other activities, throughout Project ICAN. It provided the teachers with opportunities to plan NOS/SI lessons and implement their lesson plans, and to observe their peers' presentations in the context of various science content and teaching approaches. The teachers also received verbal and written feedback from peers and the authors after each microteaching lesson.

Classroom Practice and Feedback

The aim of reflection in teacher education is for teachers to gain a deeper understanding of their teaching practice (Abell, Bryan, & Anderson, 1998). Helping teachers inquire into their own teaching and think critically about their work is important to enhance their practice (Carter & Anders, 1996). Research on teacher professional development reveals that experienced teachers are often resistant to change and innovation (van Driel, Beijaard, & Verloop, 2001). As a way to reduce such resistance, teachers need to share their curriculum materials and activities and learn from, and with, each other as colleagues (van Driel et al., 2001). During the academic year of Project ICAN, the teachers were given a classroom reflection assignment each month. A classroom reflection protocol required them to describe and evaluate one of their lessons aimed at teaching NOS and/or SI. The teachers brought issues about their classroom practice, as well as their classroom reflection assignment, to monthly meetings and shared them with each other. The teachers also were asked to submit videotapes or audiotapes of one of their lessons focused on teaching NOS and/or SI. The first and second authors provided teachers with feedback on their classroom practice at the beginning of monthly meetings.

Curriculum Revision

One of the goals of Project ICAN was to help the teachers design NOS/SI-oriented instructional materials and/or revise existing materials. Since individual teachers' school and classroom environments were different, it was important for teachers to revise their own materials, so that the revised curriculum could best their own school and classroom setting (Akerson & Hanuscin, 2007). In addition, curriculum revision was intimately related to the microteaching lessons presented by teachers. Importantly, teachers were encouraged to revise their own curriculum materials to integrate aspects of NOS/SI within the context of traditional science subject matter. That is, we encouraged teachers to avoid teaching lessons just on NOS/SI independently of subject matter. The teachers brought their own curriculum materials to monthly meetings and evaluated them first for inclusion of aspects of NOS/SI and then selected five activities to revise for teaching NOS/SI.

Assessment Practice

Teachers usually do not regard NOS/SI as content that they should assess in the same manner as other subject matter knowledge (e.g., photosynthesis). From research, it is clear that teachers lack resources and experience for assessing understandings of NOS/SI (Abd-El-Khalick et al., 1998). As a result, teachers are highly unlikely to attempt to assess aspects of NOS/SI even after they have addressed NOS/SI in planned lessons. Teachers need to know how to assess students' understandings of NOS/SI in various contexts (e.g., performance-based contexts, integration with science content). The teachers were given a variety of instruments that assessed one's understandings of NOS/SI, which was followed by a discussion on how to assess NOS/SI. They were then asked to develop assessment items that they could use, with their students, for lessons they would teach. For their microteaching lessons, they were asked to make a specific plan for assessing students' understanding of NOS/SI in their lesson plans.

Data Collection Procedures and Data Analysis

Teachers' and Students' Understandings of NOS/SI

The teachers' views of NOS/SI were assessed by the Views of Nature of Science Form D (VNOS-D) and Views of Scientific Inquiry (VOSI) instruments. Both of these instruments are open-ended and assess the following aspects of NOS (Lederman, 2007; Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002):

- Tentativeness
- Creativity
- Observation and inference
- Subjectivity
- Functions and relationships of theory and law
- Socially and culturally embedded
- Empirically based

The aspects of scientific inquiry (NRC, 2000) assessed were the following:

- Scientific investigations all begin with a question, but do not necessarily test a hypothesis.
- There is no single set and sequence of steps followed in all scientific investigations (i.e., there is no single scientific method).
- Inquiry procedures are guided by the question asked.
- All scientists performing the same procedures may not get the same results.
- Inquiry procedures can influence the results.
- Research conclusions must be consistent with the data collected.
- Scientific data are not the same as scientific evidence.
- Explanations are developed from a combination of collected data and what is already known.

Teachers completed pre- and post-tests of these questionnaires at the beginning of the summer orientation and at the end of the summer institute. The teachers also administered the VNOS and VOSI instruments that were revised for either elementary or secondary level students to one of their classes at the beginning (September) and at the end of the academic year (June). It is noteworthy to discuss our data analysis scheme for views of NOS/SI. The grading scheme for NOS was as follows: (1) a response that clearly reflected a naïve view of NOS/SI (1 point); (2) a response that reflected both naïve and informed views, or a response that partially reflected a more informed view of NOS/SI but was poorly articulated (2 points); (3) a response that clearly reflected a more informed view of NOS/SI and that was well articulated (3 points). In this scheme, a naïve view refers to the one that is completely inconsistent with contemporary conceptions of NOS/SI. In contrast, an informed view refers to one that corresponds with contemporary views of NOS/SI accepted by science philosophers, scientists, and science educators. The results from each year were merged together. Therefore, the results in this report present the summary of all ICAN teachers during 5 years.

Teachers' Pedagogical Knowledge

The teachers' pedagogical knowledge of NOS/SI instruction was assessed from their microteaching lessons. In years 4 and 5, ICAN teacher groups presented three microteaching lessons (instead of the two in previous years) during the program (i.e., in January, May, and July). Each teacher group also turned in a lesson plan for each microteaching lesson. All lessons were videotaped for analysis. The data analysis scheme for teachers' pedagogical knowledge was as follows: (1) *Implicit*—This way of teaching NOS and/or SI is related to doing science and/or only science content. Lessons do not incorporate how to address the target aspects of NOS and/or SI, so there is no explicit attempt to teach NOS and/or SI; (2) *Didactic*—Aspects of NOS and/or SI are didactically addressed without a reflective discussion on meanings of NOS and/or SI embedded in a classroom activity; and (3) *Explicit/Reflective*—Aspects of NOS and/or SI are addressed through a reflective conversation with students by making connections to students' activities within the lessons.

Results

Teachers' Understandings of NOS

Overall, a large majority of the teachers showed enhancement in their NOS conceptions (Table 7.1). On the post-test, teachers who held naïve views of each aspect of NOS were less than 10% as compared to about 30% on the pre-test. The increase in the frequency of teachers holding informed views ranged from 27% on the observation vs. inference aspect, to 37% on the subjective aspect of NOS. With respect to the tentative aspect of NOS, 48% of the teachers (vs. 17% from the pre-test) held informed views. Teachers stressed how new information and new perspectives played a role in developing scientific knowledge:

Table 7.1 Percentage of each score on the teachers' views of NOS in the pre- and the post-test

	Tentative NOS		Creative NOS		Observation vs. inference		Subjective NOS		Empirical NOS	
Score	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Informed	17	48	30	64	49	76	28	65	50	83
Transitional	49	47	40	26	25	21	38	37	36	14
Naive	34	5	30	10	26	5	34	8	14	3
Total	100	100	100	100	100	100	100	100	100	100

> Yes, [scientific knowledge may change.] In my opinion science is a living study. By that I mean it may change as our ability to observe and investigate improves over time. In addition, our way of thinking and interpreting data is developing and changing. There are many examples of changing scientific knowledge. Examples of changing scientific knowledge are as old as the Earth centered universe and the flat Earth theory. Also, recently, Einstein's theory overturned Newton's theories.

Sixty-four percent of the teachers (vs. 30% from the pre-test) exhibited informed views of the creative aspect of NOS in their responses to the post-test. Initially, 30% of teachers did not understand the creative and imaginative aspect in observation and data analysis, stating that "scientists use creativity in planning only, but creativity in observation and analyzing data is a kind of lying. That is not science." But, such views were shifted to a more informed view:

> Imagination is saying "what if" and then constructing a scenario. Certainly this occurs in the planning and experimenting phases. During the observations, the scientist may as well ask "what if" questions and revise the experiment or continue with the original "what if" and remain as objective in his/her observations. During the analysis of data the imagination still has a role. Analysis requires taking in different perspectives and using new paradigms. Reporting also can accommodate the imagination in a different presentation manner or the way the results are presented.

On the post-test, a majority of the teachers (76% vs. 49% from the pre-test) clearly understood that scientists use both observation and inference when they developed knowledge. For example, when asked how scientists knew that dinosaur really existed, a teacher had put it:

> Scientist used the term dinosaurs to label a group of bones that appear to have several things in common. Although we do not have "real" evidence of their appearance, scientists are able to use technology to determine the age and make-up of the bones. The information gathered allowed scientist to infer and make the conclusion that they existed many years ago.

Sixty-five percent of the teachers (vs. 28% from the pre-test) exhibited informed views of the subjective aspect of NOS. Prior to instruction, most of the teachers believed that scientists reach different conclusions because they have different data, stating that "science is subjective in that each scientist has access to different data and evidence." These responses changed drastically during the program. For example, a teacher believed that scientists disagreed about what caused the extinction of dinosaurs even though they all had the same information because "different people make different inferences based on their life experiences, education, and cultural surroundings." When asked how certain scientists thought about the way dinosaurs looked, one teacher stated that:

> There is no guarantee that dinosaurs look the way we think they do. Scientist's knowledge about dinosaurs is based on assumptions and logical guess. Everything scientists use know and use for making connections are based on second hand knowledge and not first hand eyewitness testimonies.

Eighty-three percent (vs. 50% on the pre-test) of the teachers exhibited informed views of the empirical aspect of NOS in their responses to the post-test. They clearly understood that empirical evidence from systematic and scientific investigations is necessary for developing scientific knowledge. For example, one teacher stated “through careful observations and research by using a systematic method, scientist collect data. This data was then analyzed and interpreted. Without empirical evidence, it can’t be scientific.”

Teachers’ Understandings of SI

About half of the teachers initially held naïve views of SI (Table 7.2). On the post-test, the frequency of naïve views decreased ranging from 6% to 35%. The increase in the frequency of informed views ranged from 18% in the views of experiment to 37% in the multiple interpretation aspect of SI. With respect to the multiple methods aspect of SI, 50% of the teachers (vs. 20% from the pre-test) held informed views. Teachers shifted from a belief in “A scientific single method” to multiple scientific methods:

> Yes I think that scientific investigation can follow more than one method, because we are humans and there are no two a like. Research can be done in a variety of ways, sometimes it what is right in front of you, like the person who had an interest with birds. This lead an observation on types of beaks and their association with the food they eat. This method had a different beginning, it started with observations, that later made a prediction and drew a conclusion. Another method to researching can be based on testing a hypothesis by manipulating independent variables. For example, in the pendulum activity, you need to manipulate the length of a string by keeping other variables constant to test the effect of the length of a string on the pendulum period.

In response to the multiple interpretation aspect, 43% of the teachers initially held naïve views, but in the post-test, the frequency of naïve views decreased to 11%. Sixty-three percent of the teachers clearly understood that scientists may not necessarily reach the same conclusion with the same data and the same procedure:

> Scientists who ask the same question and follow the same procedures might not always end up with the same conclusion. Factors that motivate the research and the personal philosophies and values of the scientists can also make a difference in conclusion. NPR recently reported a story about a study of the popular club drug, ecstasy. The research was conducted by a group of researchers associated with a movement to keep young people off of drugs. The report pointed out several exaggerations and errors that led to the article being retracted.

Table 7.2 Percentage of each score on the teachers’ views of SI in the pre- and the post-test

	Multiple methods		Multiple interpretation		Data vs. evidence		Data analysis		Views of experiment	
Score	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Informed	20	50	26	63	23	47	19	42	17	35
Transitional	23	33	31	26	25	34	67	52	19	30
Naive	57	17	43	11	52	19	14	6	64	35
Total	100	100	100	100	100	100	100	100	100	100

With respect to the data vs. evidence aspect, 47% of the teachers (vs. 23% from the pre-test) clearly understood the difference between data and evidence on the post-test:

> There is a difference with "data" which is facts, figures as for "evidence" which is about proof hard core findings. Data is only a collection of information which can also contain error. As for evidence it is the proof or the final findings that can help to put weight to your hypothesis. Scientists can take the same data as evidence for different hypotheses.

With respect to the data analysis aspect of SI, prior to the program only 19% of teachers expressed the view that data analysis should be geared toward answering a given research question rather than just dealing with data to find something. After the program, 42% of the teachers exhibited such informed views of the data analysis aspect of SI:

> Data analysis involves a systematic examination of all the information that was collected on a particular subject and it is the process of finding an answer to a question or a missing link to complete a question or problem.

There was the least improvement in views related to the role of experiments in science. More than half of the teachers initially confused an investigation with an experiment. After the program, 35% of teachers still could not resolve this confusion. When asked if observing 100s of different types of birds' beaks and their food was an experiment, they stated that:

> Yes, I consider this person's investigation to be an experiment, because again they concluded by investigating through careful observation. The investigation help to determine a link between the shapes of the beaks to the types of food a bird ate.

Only 35% of teachers clearly grasped the meaning of an experiment on the post-test:

> I don't consider this to be an experiment for several reasons. First, the investigator does not have control over natural factors. There is very little to no manipulation of factors (e.g., birds' beaks). Actually, this investigation is another type of scientific method because the person might not be able to control or manipulate natural factors.

Students' Understandings of NOS

Students' VNOS and VOSI questionnaires were collected from 236 teachers. As mentioned earlier, the average size of the teachers' classes was 22 and the average number of classes that the teachers used for project activities was 4. The population that Project ICAN affected was about 23,000 students. However, each teacher was asked to collect pre- and post-test questionnaires from only one of their classes, about 5,700 students' questionnaires were collected and analyzed to represent the population.

After the program, the improvement of students' informed views of NOS ranged from 8% on the tentative aspect of NOS to 21% on the subjective aspect of NOS (Table 7.3). On the post-test, about 15% of students moved from naïve views to

Table 7.3 Percentage of each score on students' views of NOS in the pre- and the post-test

	Tentative NOS		Creative NOS		Observation vs. inference		Subjective NOS		Empirical NOS	
Score	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Informed	3	11	5	21	27	44	19	40	47	65
Transitional	64	73	51	48	36	31	36	33	43	28
Naïve	33	16	44	31	37	25	45	27	10	7
Total	100	100	100	100	100	100	100	100	100	100

either transitional or informed views of NOS, except for the empirical aspect in which few students originally held naïve views. It should be noted that the results in Table 7.3 were from K-12 students. In general, students' improvement of their views of NOS increased as their grade levels were higher.

With respect to the tentative aspect of NOS, 33% of students believed that scientific knowledge is a set of true facts on the pre-test:

> No, I do not think that the science textbook and the information in it will never change. For instance, the person who discovered the Newton will always be the person who discovered Newton.

On the post-test, the frequency of naïve views decreased from 33% to 16% and 11% of the students (vs. 3% in the pre-test) held informed views of the tentative aspect of NOS:

> Yes, scientists are making new discoveries every day and what may have been thought of as true in the past become subject to debate and sometimes is even tossed out as factual…

Forty-four percent of the students on the pre-test disagreed that creativity and imagination of scientists is involved in during investigations and believed that scientists' creativity and imagination is involved only in planning or designing an investigation. Few students accepted the use of creativity in observation and data analysis:

> Creativity is used in the planning stage. The other parts of the investigation must be objective.
>
> The planning and experimenting stages are much capable of creativity…creativity in observation, analyzing data and reporting is a form of lying that's not science…

On the post-test, 21% of students (vs. 5% in the pre-test) seemed to understand the role of scientists' creativity and imagination in doing science:

> Yes, you would have to use your imagination all the time to be a scientist I think. Scientists are the people who have to experiment with things that they might not have a lot of knowledge about like putting together a dinosaur. They had no pictures of how they looked and to put them together I think they used facts (maybe about reptiles), opinions, inferences, and of course their imagination.

With respect to the observation vs. inference aspect of NOS, 37% of students on the pre-test did not realize the role of inference in doing science. In the post-test, the frequency of naïve views decreased from 37 to 25%. Almost half of the students (44%), as compared to 27% in the pre-test, expressed an adequate understanding of the distinction between observation and inference like the one below:

> . . .dinosaur had to be reconstructed based on other information such as bones, relatedness to existing creatures today, and the environment in which they existed. In other words, scientists can imagine what dinosaurs looked like with the data they collected.

Forty-five percent of students initially held naïve views in terms of the subjective aspect of NOS. They believed that scientists should reach the same interpretation with the same data stating that: “I think they might disagree because they interpret the facts wrong” and “They disagree because some facts might not be true.”

Thirty-six percent of students believed that scientists could have different interpretations with the same data, but they did not understand the role of scientists’ different background knowledge (e.g., scientific theories) in observations and interpretations. Only 19% of students held informed views in the pre-test.

In the post-test, 27% of students (vs. 45% in the pre-test) still exhibited naïve views. Forty percent of students (vs. 19% in the pre-test) understood that scientists could interpret the same data differently due to their different background knowledge when asked why scientists disagree about what caused the dinosaur extinction to happen:

> [Scientists disagree] because scientists interpret the same information differently. They have different perspectives by which they understand or view the same information
>
> . . .given data, observations of the changes that occurred on the earth, weather estimates they have made inferences only. Inferences are subject to cultural and social references of the time.

With respect to the empirically based aspect of NOS, only 10% of students did not realize the importance of empirical data in doing science in the pre-test. Forty-three percent of students believed that empirical data were involved in doing science but their ideas were not sophisticated. Almost half of students already expressed informed views.

On the post-test, 65% of students understood the importance of empirical data to a scientific investigation. One student stated that “Science is a method of studying the natural world. . .systematic experimentation to gain knowledge about events in nature. . .scientists have collected bones and fossil evidence to support their existence. . .”

Students’ Understandings of SI

After the program, the enhancement of students’ informed views of SI ranged from 5% on the data analysis aspect to 20% in the multiple methods aspect (Table 7.4). About 20% of students shifted from naïve views to either transitional or informed views of SI. Similar to NOS, higher grade level students showed more improvement of their views of SI.

Table 7.4 Percentage of each score on students' views of SI in the pre- and the post-test

	Multiple methods		Multiple interpretation		Data vs. evidence		Data analysis		Views of experiment	
Score	Pre	Post	Pre	Post	Pre	Post	Pre	Post	Pre	Post
Informed	6	26	13	33	13	29	5	10	5	17
Transitional	39	33	29	36	24	30	35	34	26	34
Naïve	55	41	58	31	63	41	60	56	69	49
Total	100	100	100	100	100	100	100	100	100	100

With respect to the multiple methods aspect of SI, more than half of the students did not have a clear idea about scientific methods, stating that:

> No, [scientific investigations cannot follow more than one method] I think that an investigation is just to gather information and observing what you are investigating.

Few students (6%) clearly understood that scientists use multiple methods that all can be scientific. In the post-test, 41% still held the scientific method view. Twenty-six percent of students (vs. 6% in the pre-test) were aware that there are scientific investigations can follow more than one method:

> Yes, they (scientists) follow more than one method. For example, they do the experiment by controlling and manipulating variables. On the other hand, they can do an investigation by observing something like a bird investigation above. The person just observed hundreds of different types of birds and their food and drew a conclusion.

More than half of the students (58%) on the pre-test attributed scientists' different interpretations of the same data to their mistakes by holding the view that scientists should reach the same conclusion with the same observations:

> No, [scientists will not necessarily come to the same conclusions] because there is always human error. If not, they should come to the same conclusion.

On the post-test, 31% of students exhibited the same naïve views as in the pre-test. Thirty-three percent of students (vs. 13% on the pre-test) expressed informed views of the multiple interpretation aspect of SI in the post-test. They believed that:

> No, [scientists will not necessarily come to the same conclusions] because many things can affect a person's answer such as their prior knowledge, their surroundings, their way of thinking, and their biased answers.
>
> No, [scientists will not necessarily come to the same conclusions] because each person thinks differently, and interprets differently. Also, scientists have to use their imagination, and they may not imagine the same thing.

In response to the data vs. evidence aspect, 63% of students confused data with evidence on the pre-test, but in the post-test, 41% of students kept holding naïve views of the data vs. evidence aspect. Twenty-nine percent of students (vs. 13% on the pre-test) expressed informed views:

> Data and evidence are same to me, just with different names. They're both information to back up or support something with. [pre-test]
>
> Data is something that you collected from your investigations. But, evidence is part of data that you use to support or prove a point. [post-test]

There was little improvement in the data analysis aspect of SI. More than half of the students held naïve views on the post-test and only 10% of students exhibited informed views that

> Data analysis means to find a pattern from data or observations to answer a research question or to test a hypothesis.

Sixty-nine percent of the students initially did not know what an "experiment" meant. After the program, the frequency of students holding naïve views decreased from 69% to 49%. Seventeen percent of students clearly understood the meaning of an experiment. When asked if the investigation in which a person observed different types of birds who eat different types of food was an experiment, they stated that "I don't consider it an experiment because the person is not testing a hypothesis by manipulating birds' beaks and controlling other variables."

Teachers' Pedagogical Knowledge for NOS/SI

Table 7.5 and Figure 7.3 shows how the ICAN teachers changed their lessons from Level 1 (Implicit) to Level 2 (Didactic) to Level 3 (Explicit) lessons. The teachers initially adopted an implicit teaching of NOS/SI in which students (peer teachers

Table 7.5 The frequency of each level in each microteaching session

	1st microteaching			2nd microteaching			3rd microteaching		
	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3	Level 1	Level 2	Level 3
Middle/Ele.	4	2	0	1	2	4	0	1	5
Secondary	4	1	2	1	4	2	0	2	4
Total	8	3	2	2	6	6	0	3	9

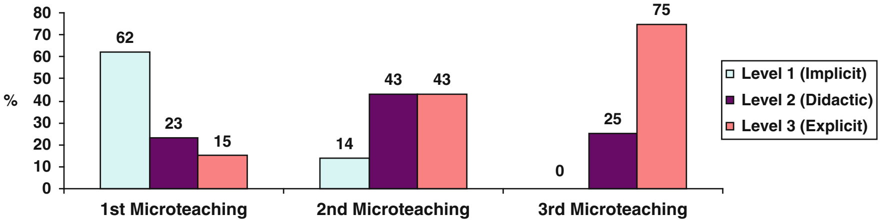


Fig. 7.3 Changes from implicit to didactic to explicit–reflective teaching approaches through three microteaching sessions

in the microteaching context) only engaged in doing activities without discussing NOS/SI. About 60% (8 out of 13) of teacher groups presented Level 1 lessons at the first microteaching practice.

On the second lesson, the frequency of Level 1 lessons decreased to 14% (2 out of 14), but Level 2 and Level 3 lessons both increased to 43% (6 out of 14). Finally, during the third microteaching session, 75% (9 of 12) and 25% (3 of 12) of the ICAN teacher groups presented Level 3 and Level 2 lessons, respectively. No Level 1 lessons were identified. The change from six groups (43%) in Level 3 in the second microteaching session to nine groups (75%) indicates that around 30% of the teachers improved their pedagogical knowledge of NOS/SI instruction.

The results indicate that through three microteaching sessions the teachers improved their pedagogical knowledge of how to teach aspects of NOS/SI. They clearly connected what students did in the lessons with actual scientific practice. Not only did the teachers find opportunities to integrate NOS/SI in their lessons, but they intentionally had students exposed to certain activities to afford opportunities to explicitly discuss NOS/SI.

Discussion and Implications

The research presented provides a clear example of how to build teachers' capacity to address NOS/SI through systematic, research-based professional development. Of particular importance is that Project ICAN is virtually the only effort that has included teachers' knowledge, teachers' practices, and students' learning within a single effort. The results of the study indicate that Project ICAN significantly helped teachers improve their understandings of NOS and SI and their pedagogical knowledge of NOS and SI instruction. With respect to NOS, teachers' percentage gains for informed views of each aspect of NOS ranged from 27 to 37% comparing the pre- to the post-test. About 90% of the teachers possessed either transitional or informed views of each aspect of NOS and only 10% or fewer teachers held naïve views of each aspect of NOS. Similarly, a substantial number of teachers, ranging from 18 to 37%, shifted from naïve or transitional views of each aspect of SI to more informed views.

The analysis of student data indicates that project ICAN did not influence students' understandings of NOS and SI as much as teachers. However, clear improvement of students' views was noted. The percentage gains for informed views of each aspect of NOS ranged from 8 to 21% and for SI from 5 to 20%. Although only about a third of students possessed informed views of NOS and SI, this amount of improvement is considerable and promising. It is also important to realize that students rarely move from naïve levels to informed views immediately. Typically, they would improve from naïve to transitional and transitional to informed. Long-term intervention is necessary for substantial change in students' views of NOS (Khishfe & Abd-El-Khalick, 2002). The duration of Project ICAN for students was really only 1 year long, thus we could not expect the impact of teachers' improved understandings of NOS and SI and their pedagogical skills to immediately improve students' understandings of NOS and SI. However, it was clear toward the end of the project that teachers were capable of providing their students with explicit instruction for NOS/SI.

The analysis of teachers' microteaching lessons indicates that 80% of the teacher groups were not able to develop a lesson plan and implement a lesson using an explicit approach to NOS/SI during their first practice lesson. Targeted aspects of NOS and/or SI were not explicitly addressed or didactically delivered. By the third lesson, however, 75% of the teacher groups illustrated explicit instruction for NOS/SI (Level 3). They incorporated explicit and reflective discussions on aspects of NOS/SI into their teaching of traditional subject matter knowledge. Although it appeared to be a difficult task to implement explicit teaching about NOS/SI, 25% of the teacher groups remained as didactic (Level 2), while none of the groups followed an implicit approach (Level 1) by the third lesson. From the analysis of teachers' microteaching lessons, the improvement from Level 1 to Level 2 to Level 3 seems to be a developmental continuum of pedagogical knowledge of NOS/SI instruction. There are two critical changes that need to occur in order to implement explicit NOS/SI instruction.

First, teachers need to realize that explicit teaching is more effective than implicit instruction. Even though several explicit activities and explanations for the difference between explicit and implicit NOS/SI instruction were provided early, in the first microteaching session 62% of the teacher groups exhibited implicit instruction, which is consistent with previous findings (Abd-El-Khalick et al., 1998). The teachers initially believed that students could learn about NOS/SI by only *doing* science (Abd-El-Khalick et al., 1998). For example, one group of teachers attempted to teach the empirically based aspect of NOS, but without any explicit instruction they just engaged their peers in making observations. Later one of the teachers asked "The one I get very confused on is empirically-based. . .how is that different from regular observations?" Extensive experience is needed for teachers to realize that they are adopting an implicit approach, which is not effective in teaching NOS/SI, and to understand that doing something does not necessarily guarantee knowledge about what one is doing.

Second, teachers need to be aware that a student-centered approach to explicit instruction is more effective than a didactic approach. In the second microteaching session few lessons were classified as implicit. Most of the teachers appeared to realize they used an implicit teaching approach during the first microteaching session. However, discerning this implicit approach was not sufficient for some of the teachers to then implement explicit NOS/SI instruction. Many of the groups that used implicit teaching in the first microteaching session adopted a didactic approach in the next session. This means they intended to explicitly teach NOS, but failed to address target aspects of NOS/SI in the explicit manner advocated by Project ICAN. A short and didactic discussion for NOS/SI was assigned at the end of a lesson rather than a reflective and interactive conversation with students.

The pedagogical content knowledge (PCK) model for NOS (Schwartz & Lederman, 2002) defines a teacher's PCK for NOS as the integration of NOS knowledge, subject matter knowledge, and pedagogical knowledge. This developmental continuum of pedagogical knowledge in the present study elaborates this PCK model for NOS. NOS-specific pedagogical knowledge should include knowledge about the difference between an implicit and an explicit approach and the difference between a didactic and an explicit, reflective approach.

The present results support the effectiveness of an explicit approach to teaching about NOS and SI and pedagogical knowledge of NOS and SI instruction (Abd-El-Khalick & Lederman, 2000a; Akerson et al., 2000; Khishfe & Abd-El-Khalick, 2002; Moss et al., 2001; Ryder et al., 1999). However, it should be emphasized that the analysis of microteaching lessons clearly presented that engaging teachers in explicit NOS/SI instruction does not necessarily guarantee that teachers can implement explicit NOS/SI instruction. The model of professional development shown in Fig. 7.2 appears to be successful in helping teachers shift from implicit to explicit instruction for NOS and SI. Planning and presenting three microteaching lessons seemed to help teachers inquire into their own teaching practice and critically reflect on their work. After each microteaching session, teachers became aware of their implicit or didactic teaching by reflecting on their own practice and comparing it to other groups' lessons. The teachers planned and presented their microteaching lessons three times and had the opportunity to observe and discuss about 19 to 20 peer groups' lessons. It seems that the microteaching sessions helped the teachers become familiar with teaching about NOS and SI. Providing additional model lessons after each microteaching session, in conjunction with other activities (e.g., science internship, classroom teaching experience, curriculum revision, and assessment practice), appeared to help teachers elaborate their content knowledge and pedagogical knowledge. One teacher's comment on her first microteaching presentation is an example:

> I think the last lesson, when we had the group who did creatures making with celery and carrot. . .That helped a lot and they were very explicit and then N (the first author) and J (the second author) explained a lot more. Once that's done, I understood how to be explicit.

In guiding the teachers' microteaching lessons, it was also important to ask them how they would assess their students' understandings of NOS. Having teachers' consider how they would assess students' understandings of NOS/SI revealed their mindset about implicit teaching teaching as well. One group of teachers was planning to teach the creativity aspect of NOS in the context of teaching the evolution of human skulls. They decided to provide students with data about human skulls of earlier human forms and modern human beings and to have students construct a model of a future human skull based on the given data. They planned to have a discussion at the end of their lesson to address the idea that scientists use their creativity and imaginations in doing science. Their plan appeared to be explicit and reflective. However, this group was trying to assess students' understandings of the creative aspect of NOS by evaluating future human skull models that students are going to create. It was more about students' ability (i.e., creativity), which was *doing* science, than their knowledge of the creative aspect of NOS. In short, creativity was used, but this is different than knowing that creative imagination is an integral part of all scientific knowledge. When teachers were asked if they attempted to assess students' abilities to use data, they immediately denied it and claimed that their intention was to assess students' understandings of the creative aspect of NOS. However, soon they realized that, unlike their intention, they attempted to measure students' creativity. In the lesson plan for the following microteaching lesson, they planned to ask the questions listed below:

- Did your group use their imagination/creativity in creating your models?
- Do you feel that scientists use creativity in creating models?

Therefore, requesting teachers to make a plan for assessment of students' understandings of NOS/SI plays a role in stressing that NOS/SI should be a cognitive outcome (Bell et al., 2000), and in diagnosing their NOS/SI knowledge and NOS/SI-specific pedagogical knowledge.

The results from Project ICAN indicate that teachers improved their NOS/SI instruction as evidenced across three microteaching lessons. They became proficient at connecting what students did in their lessons to what scientists do, illustrating certain aspects of NOS and SI. Not only did they find opportunities to integrate NOS/SI from student activities in their lessons, but they also intentionally had students exposed to certain situations of *doing* science, which afforded meaningful discussions on aspects of NOS and/or SI. In connecting aspects of NOS/SI to *doing* science, it is not surprising that the difference between observations and inferences was the most frequent aspect of NOS that the teachers addressed. Ten out of 17 Level 3 lessons included this aspect. The teachers may have felt comfortable incorporating this aspect of NOS within their lessons because making observations and inferences are common features of any investigations and many science curricula.

Implications for Professional Development

The findings from Project ICAN imply that professional development programs should provide teachers with several opportunities to make plans and implement lessons on aspects of NOS and SI. Microteaching sessions can be a meaningful strategy to improve teachers' content knowledge and pedagogical knowledge about NOS and SI.

Although we led teachers through explicit NOS/SI activities designed to help them improve their understandings and provided them with model lessons to explain how to teach about NOS and SI in an explicit manner, 60% of the teacher groups did not explicitly address aspects of NOS and/or SI at their first microteaching lesson. More importantly, they believed that they were successfully teaching about NOS and SI. Therefore, professional development programs should help teachers recognize their implicit teaching approach through microteaching or lessons taught, and reflected upon, in real class settings.

However, it must be emphasized again that the recognition of an explicit teaching approach does not guarantee that a teacher will develop the ability to successfully provide explicit instruction on NOS and SI. Unless teachers know how to help students reflect on the target aspect of NOS and SI, they might resort to a didactic approach to teaching about NOS and SI. Comparing their own practice to others, teachers seemed to take advantage of peer groups' microteaching lessons in grasping how to teach about NOS and SI explicitly.

In addition to the importance of microteaching sessions, professional development programs should be designed with a long duration. Short, "boot camp" types of professional development that might take several weeks during the summer will doubtfully be successful. It is not a short journey for teachers to change their understandings of NOS and SI, as well as their ability to communicate these understandings to students (Akerson & Hanuscin, 2007). At the end of the year, some ICAN teachers' understandings of certain aspects of NOS and SI were still limited, and 25% of the teacher groups were not able to exhibit explicit teaching about NOS and SI, although they did shift from implicit to didactic teaching.

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Chapter 8
The Nature of Scientists' Nature of Science Views

Renee' Schwartz

What Scientists Say. . .

No one would doubt that scientists have insights into science and the community that produces scientific knowledge. Scientists have experiences and relationships with science that non-scientists simply do not have. Tapping into scientists' ideas about what science is and how scientists do their research can be a valuable way to better understand the nature of science [NOS], the scientific community, and how authentic experiences might shape ideas about science. Finding out "what scientists say" can be as easy as having a conversation or as difficult as. . .having a conversation. It all depends on the people involved. One of the most rewarding experiences I have had as a researcher was studying scientists' views of NOS and scientific inquiry (Schwartz, 2004; Schwartz & Lederman, 2008). The research questions were straightforward: What are scientists' epistemological views of science? Do their views vary depending on the science context? These were pressing questions of the late 1990s, till date. Many discussions about teachers' NOS views are followed with inquiries such as, "What do scientists say in response to the same probing questions about NOS?" How does a scientist answer the question, "What is science?" This chapter presents interview excerpts from two research scientists who answered this question, and other questions, as participants in a study to explore the nature of scientists' NOS views.

Nature of Science for K-12 Learners

The NOS framework used in this study is that which has guided many empirical studies on NOS views. I draw from the work synthesized by Lederman (2007)

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who describes NOS as a "critical educational outcome [included in] various science education reform documents worldwide" (p. 831). He supports that among science educators concerned with K-12 education, there exists greater consensus about NOS than disagreement. It is the agreed-upon aspects of NOS that are advocated as appropriate and important for K-12 learners (Abd-El-Khalick & Lederman, 2000; Lederman, 2007; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003), and thus, are what guided the work I conducted with scientists. These aspects describe scientific knowledge as a product of human intellect. That scientific knowledge is *inherently tentative and subject to change*, yet based on *observation and inference* from the *empirical world*; scientific knowledge is a product of *creativity, as well as theory-laden and subjective decisions and interpretations*, which is *embedded within the society and culture* of scientists' practices; and *scientific theories and laws* are two types of scientific knowledge. Also examined in this study, and embedded within the excerpts presented in this chapter, are ideas about scientific inquiry (e.g., no single scientific method, justification of knowledge claims) and scientific models. These aspects should not be considered discrete traits, or an all-inclusive list that describes all of science. Rather the targeted NOS aspects are those considered relevant for children and young adults, as well as the general public. Moreover, the aspects are related to and dependent upon each other. Our goal is for students to develop a web-like structure of NOS knowledge that demonstrates connections, relationships, and examples from multiple science contexts.

What Are Scientists' NOS Views?

There have been extensive studies of scientists' work that provide details and ethnographic accounts of authentic communities of science practice (e.g., Knorr-Cetina, 1999; Latour & Woolgar, 1979). These works help us to understand the world of scientists and lend themselves to interpretations of how scientists might think or reason within that world (or worlds). Relatively few empirical studies have been conducted from a science education perspective that explore how scientists describe "what science is" and the development of scientific knowledge. Some reports suggest that scientists, like teachers and students, do not necessarily hold epistemological views that align with currently accepted views advocated for science education (Behnke, 1961; Glasson & Bentley, 2000; Kimball, 1967–68; Pomeroy, 1993; Schmidt, 1967; Schwartz & Lederman, 2008). Studies that have used paper/pencil surveys to compare scientists and science teachers offer some information about commonalities and differences among these groups (Behnke, 1961; Kimball, 1967–68; Pomeroy, 1993; Schmidt, 1967). Behnke (1961) developed statements that represented different views about science, science and society, the scientist and society, and the teaching of science. He found that scientists differed in their views from science teachers, yet still there was variance within the group of scientists. He reported that neither the teachers nor the scientists held views entirely consistent with those accepted at the time of the study. Schmidt (1967) used the *Test on Understanding Science* [TOUS] to examine students, science teachers, and scientists' views about science. He reported that the scientists averaged only 83% on the TOUS. His results also indicated that some high school students and teachers scored higher than scientists on the TOUS, suggesting they had a "better" understanding of NOS than the scientists, as measured by the TOUS instrument. Pomeroy (1993) used a Likert-type instrument to compare the views of scientists and teachers. She identified the logicoempiricist view of science as the "traditional" view, or the belief that scientific knowledge progresses only through inductive methods based on observation and controlled experimentation. In contrast, Pomeroy (1993) described the "non-traditionalist" view as that which recognizes that "dream, intuition, play and great inexplicable leaps as potentially part of scientific method" (p. 262) are a part of science. This view also recognizes that objectivity is unobtainable. She administered a 50-item Likert survey, and reported that the scientists in her sample tended to hold traditional views of science, as did many of the high school science teachers. Using the 29-item Nature of Science Scale [NOSS], Kimball (1967–68) determined the scientists and science teachers in his sample held similar, yet "inadequate," views about science as measured by the NOSS. All these studies suggest that scientists do not necessarily hold views about NOS that agree with positions measured within the paper/pencil surveys. These results are interesting, but what do scientists actually say about what science is?

More informative accounts of scientists' views of NOS have been gathered through open questionnaire and/or interview methods. Reports from Glasson and Bentley (2000), Schwartz and Lederman (2008), and Wong and Hodson (2009) describe the range in scientists' perspectives, some aligning with contemporary views advocated for science education; some maintaining logicoempiricist views; and many mixtures in between. These studies also report that when scientists talk about what they do, the picture that emerges is not altogether aligned with the picture created through science curricula and classrooms. Glasson and Bentley (2000) interviewed six scientists who also gave presentations at a conference. They examined the NOS portrayed in each setting. They reported fairly good consistency for each scientist in how NOS was portrayed during the presentation as compared to the interview, yet there were differences among the scientists that ranged from positivist to post-positivist ideas: although, most had mixed views that drew upon individual experiences. The findings from the 13 scientists interviewed by Wong and Hodson (2009) and the 24 scientists surveyed and interviewed by Schwartz and Lederman (2008) indicate that scientists, regardless of discipline, are able to articulate sophisticated, yet varied views that are bound by the context of the individual scientist. They may see variation in scientific methods and inference in data interpretation, yet some scientists hold fast to the notion that all investigations are hypothesis-driven and that given enough data, there can only be one conclusion.

Reflection on Practice

Why is there so much variation in scientists' views? Glasson and Bentley (2000) offer a rationale:

> The overriding view among practicing scientists is that science is essentially experimental and empirical; however, the important role of theory, the multiplicity and complexity of science methods, and the value-ladenness of science require that scientists examine the assumptions underlying their own research and what goes into the decision-making that affects research design, funding, and public acceptance of results. (Glasson & Bentley, 2000, p. 483)

Reflection on *what* science is and *how* science is done is required to discuss one's views of NOS. Such reflection requires a transition from doing science to thinking about what doing science means (Schwartz & Crawford, 2004; Schwartz, Lederman, & Crawford, 2004). Thus, scientists must detach from their role as scientists to examine their assumptions and reflect upon the nature of the knowledge and how it is developed within their own research. Few scientists are actively reflective in their daily research, and there seems to be little relation between such reflection and successful scientific practice (Elby & Hammer, 2001; Glasson & Bentley, 2000). There is also no pattern between views of NOS and success as a scientist (Schwartz & Lederman, 2008). Teachers, and researchers, need to help learners transition from the outside (a student), to the inside (a scientist), and back to the outside again (a reflective student) in order to connect what they are learning and doing in science and, as scientific inquirers, to NOS and scientific inquiry. For scientists, the change in perspective from inside to outside may be more challenging (Schwartz & Lederman, 2008). Our work with scientists indicates that scientists' NOS views are sophisticated, at least in how they are articulated. While scientists can express passionate and personal experiences, their views are varied, and not always naturally or easily accessed.

A compelling aspect of researching scientists' epistemological views comes from the process of eliciting their ideas: that is, the insights that emerge from the personal interviews. If you have ever gotten to talk with someone who is passionate about his/her work, then you know that the "interview" turns into a conversation that reveals more than the original interview questions ever would have. As researchers and educators, we can learn from this style of eliciting reflection as well as from the reflections and stories themselves.

Purpose of the Chapter

In this chapter I present how two scientists were able to examine and describe some of the assumptions of their research. They reflected upon their work and community, the decision making that occurs, and how their work is viewed and accepted by others. The work presented here demonstrates the significance of Glasson's and Bentley's claim that scientists need to examine their own research in order for us to gain a more meaningful understanding of how they view science. This chapter provides two examples. Schwartz and Lederman (2008) and Wong and Hodson (2009) recommend scientists' case studies that provide rich examples of NOS from contemporary experiences in the scientific community. This chapter offers two cases from contemporary science in the form of interview excerpts. As stated, the intrigue is in the details and the conversational style with which the two prominent scientists spoke. The biochemist/molecular biologist, Dr. Hershall, and the astrophysicist, Dr. Ross (pseudonyms), reveal their ideas about science through stories from their lives.

I contacted both Dr. Hershall and Dr. Ross as part of the pool of scientists I sought to interview as part of a large study on scientists' epistemological views of science. I did not know either one before I contacted them. Their online profiles were interesting to me as successful scientists who represented different types of science and ways of conducting their research. There were 24 scientists in the final pool, representing four broad areas (life science, earth science, physics, chemistry), multiple subdisciplines, and varied investigative methods (experimental bench science, field-based studies, correlational studies, descriptive studies, theoretical work, computer and mathematical modeling). The two chosen for this chapter represent two types of science: experimental biochemistry and theoretical astrophysics. At the start of the interviews, I reviewed my classification with each scientist (discipline area and research approach) in order to ensure I had reliably described them.

I present excerpts so that the reader may draw inferences about the nature of the scientists' NOS views. I have drawn my own interpretations, mention some here, yet detail them elsewhere (Schwartz & Lederman, 2008; Schwartz, 2004). It is my intention here to provide the voices of the scientists and the essence of the conversations we had. The interviews are not provided in their entirety. I have edited to focus on NOS-related segments. However, I occasionally include portions not directly discussing the NOS aspects. These additional excerpts contain intriguing ideas and insights into the scientists' more specific views about scientific models and the nature of scientific inquiry (e.g., acceptance of knowledge), certainly ideas that are related to NOS and worthy of our attention. I have also included excerpts where the scientists compare one type of science to another. Overall, the order in which I present the excerpts is consistent with how the interviews flowed. The reader may notice some shifting of topic as well as revisiting topics during the interviews. I have maintained the integrity of the order so that the reader gets a better sense of the comfortable conversational style of the interviews. For guidance and clarity, I provide headings and a brief introduction to most excerpts. I have *italicized* certain passages that were particularly compelling to me, as they relate to specific NOS ideas.

Dr. Hershall: A Discussion About Puzzles, Day Dreams, and Play

Dr. Hershall is a male, approximately 45 years old. He is a biochemist and molecular biologist who primarily conducts experimental bench science at a large university in the United States. He is a full professor in a biochemistry department. At the time of the interview he had 19 years' experience teaching and in research, including 15 years in a medical school. I met Dr. Hershall in his office located on a large university campus. The afternoon of the interview he had actually forgotten our meeting, and I caught him about to head home for the day. Two hours later, we wrapped up our conversation and he went home. I had not intended our meeting to last 2 h, but as you will see in the excerpts, the conversation was compelling. It was my practice to allow the interviews to go as long as the scientists were comfortable and willing to continue talking. It was quickly obvious that Dr. Hershall had a lot to say. It was a fascinating and quick 2 h. Picture the scene of a large academic office with book shelves, a large wooden desk, computer, a small wooden table, and several chairs. Dr. Hershall sat in a comfortable-looking chair at the side of this desk, rather than behind it. Many times during our conversation he would lean back, look at the ceiling, and then look at me while he continued his stories and responses to my questions.

We began discussing how he got started in science. He had been interested in environmental sciences in addition to molecular biology. During his undergraduate work, he had the opportunity to study peroxidases in pine trees, which had interesting genetic variation. "*I stayed for a master's degree and found that peroxidases work on a reduced form of oxygen, oxygen with two extra electrons. So that got me interested in the field of oxidative stress*." He began to look into defenses of infections, and continued by studying superoxide dismutase, an enzyme that removes electrons from oxygen and prevents oxidative damage. This work led him to study stroke and the notion that oxygen radicals are involved in stroke. Thus he began investigating the relationship between superoxide dismutase and stroke. In our discussion, he began by stating the big questions he was interested in. His description highlights the role of questions in guiding this scientist throughout his career:

> [It was a question of] if superoxide dismutase is protective, what does it do to . . . .why is it protective? Superoxide was actually given its name by Linus Pauling based on looking at its chemical structure and saying this should be a strong oxidant. In biological systems, it is not. It is a weak reductant. So that leaves you with a chemical question of just what does superoxide attack in cells?
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> . . .we had a visitor who talked about the endothelium derived relaxing factor. . . .I fell asleep in the middle and woke up just as [the speaker] said, "And superoxide dismutase protects this factor." So that got me very interested into paying attention. . . . . Two or three years later they identified EDRF as nitric oxide. I went and started to read a chemistry textbook I had paid 75 cents for in high school. It was a good thing it was an old one because they had taken it out of the new editions. But the product of the reaction of superoxide with nictric oxide is something called peroxinitride. They described how this is a very strong oxidant that generated other radicals. . . . .And so I wrote a paper that showed that this was a strong oxidant and was a major root of toxicity in vivo, and would explain a lot of radical damage. I was very paranoid that it was such an obvious thing that everyone would jump on this. But in fact it was ignored for several years. So there is a quote that says, *"Small ideas need protection. Great ideas are protected by incredulous people."* I like that a lot.
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> *. . .but one of the things that we did was a mistake I did in the lab***.** If you add a protein to a large concentration of superoxide dismutase, and it turned yellow. It was in the middle of the night and I saved it. It was still yellow the next morning. It turned out that the protein was modified. So we crystallized it. A friend I played soccer with said he could do the x-ray structure. So he did and he said there is something on the amino acid tyrosine, which was very surprising. Then we discovered basically you could form nitrictyrosine and that this was actually an abundant modification in many pathologic tissues. We raised antibodies to them that are used throughout the world now. Any human disease you want to look at you will find a lot of tyrosine nitration. People are working out the mechanism of what it means.

> So now I have an enzyme that I have used to protect the brain. It is catalyzing a reaction that actually ought to be bad and modifying proteins. So that would say there must be someplace where this enzyme is actually toxic. About 10 years ago, I got tired one night and went home early. I watched the news and there was a story where they announced a new discovery that causes Lou Gehrig's disease and it is an antioxidant protein. I said, "I think I know what it does!" That led to this new track where we now work on Lou Gehrig's disease. There were mutations that occur to this particular protein and the effect of it is that it gets into this one neuron that exists in your spinal cord that dies. It may wait until you are 60 years old before this starts to happen. In 2% of patients with ALS, they discovered there are mutations to this protein. So what about the other 98% of the patients? This protein is 0.5% of total cell protein, normally. It is expressed in every cell in the body before you are born. So why is it that you can survive until you are 60 or even 80 before you get the disease, and why is it only in motor neurons and not in other cells? It is a great puzzle and a puzzle that 30,000 people a year die from. So we are involved in trying to understand how superoxide dismutase causes the disease, and also whether or not this oxygen peroxinitride is involved in the process. It is highly controversial and for 10 years much more controversial than I thought it would be. We are still working our way through it and we have modified our theories a lot and made a lot of progress.

In this next excerpt, Dr. Hershall discusses how another group has attempted to discredit his work. The story is an example of how science is theory-laden and subjective, and that different groups of scientists can and will produce different explanations based on their perspectives:

S [Schwartz]: It is controversial how?

H [Hershall]: Oh, there are groups who say we can't find nitrityrosine, that the protein is forming aggregates and oxidative stress is not involved. One example is that we predict that there is a form of the enzyme that makes nitric oxide called NOS, that is found in neurons, and that it should be contributing to the disease. So you can genetically knock out the NOS gene. That was done. People cross that to mice that over express SOD and develop a motor neuron disease, or ALS. There is no effect on development to the disease. They then conclude that nitric oxide is not involved in the disease, there is nothing to what you are proposing. . .the theories we are talking about. The problem is that they knocked out exon 2, one of the exons of this protein. This protein has the most complex organization of any gene known to the human brain. It turns out that it is also expressed in muscle. The muscle form is spliced at exon 4. So they knocked out the protein that is a large part of the brain, it turns out . . .that particular knockout had no effect on development. So they did this experiment and they are making very bold conclusions from it. But it turns out that the mouse was smarter. The protein is still there. They didn't knock it out. So the experiment wasn't done. They even did an experiment where they gave an inhibitor of NOS, and it was protected. They said, "We don't believe that result." That is the kind of debate we have been going through. Just how do you interpret the experiments and what seems like a simple clean-cut experiment, they might take 2–3 years with the mice and 2–4 hundred thousand dollars, so people really want to believe their results and not want to hear that they didn't do it right. So they aren't very happy about that. But that is how science evolves.

S: So what is their reaction to the controversy?

H: It depends who you are and where you are. . . .they have their theories and mine wasn't invented at [their institution] so. . .it tends to get trashed by them, but they control the study sections. That is the debate.

According to Dr. Hershall, this particular controversy was based on who was doing the work and where they were doing the work. He mentioned there were three or four diverging theories in the field. I then asked him if there would be a situation where they would converge or one would stand out as more acceptable. His response provides an example of the relationship between the subjective and social investments of science:

S: Ok, what will it take to see, eventually, converging into one or one of these diverging off as dominant?

H: You've got to cure the disease, which is what we are working on. You've got to treat it in the human and show it in the human. We have some drugs that are approaching that stage. They are approaching phase 2. I am quite excited about it, even after 10 years. I thought I'd be on this project for 3 or 4. It is still real exciting.

S: Whoever achieves that, will the other groups automatically concede?

H: No, they just won't believe the results or will say it works by a different mechanism. The arguments will go on. They stay funded until they are ready to retire.

S: It is hard to give up?

H: Well, there are always alternatives, explore what they are. That is part of the controversy. What seems to be a really hot controversy, the resolution is somewhere in the middle usually and after a few years people forgot what they were all arguing about anyway.

The Creativity of Science: ". . .Like Building a Puzzle"

Several times in our conversation Dr. Hershall referred to puzzles. His experience with his son serves as an analogy as he explains his view of how science works:

S: So in your own work do you consider the alternatives?

H: Absolutely. So you have to weigh the evidence and experiments and consider: does this really disprove what I am thinking of or is there another explanation? If there is another explanation, what experiment can be done to test that? What can be done to test it? I view it like building a puzzle. It is hugely complex and you don't have a picture of what the overall thing is by looking at individual pieces.

> You push them together and you build different things. The analogy I like to use is about my son who was 18 months old at the time. My wife likes to put together puzzles. My son had gotten up and taken a lot of pieces of an intricate puzzle and taken them off and pushed them all together in one line. He was pulling it and was very excited and said, "look it's a choo-choo train." So when you've got a lot of different pieces, you put them together, you build a theory. *You build your own choo-choo train and you are pretty enthusiastic about it and your grants get funded. There is a lot of momentum behind this train. The idea that you have to take the pieces apart and look at them and maybe rearrange them a bit to make them look a little different is very hard to do.* You have so much involved intellectually and financially in getting this train moving in the first place. You've to hope it's not a blind track you are running into in a train wreck where all the pieces are going to fall off when you take it apart. But if you can take off one piece and bring it around to another and get a different view of the puzzle, that is perfectly fine. I think that is the way science evolves. . . .That is what your question is about: what is a law versus a theory gets very subtle between the different disciplines. In biology in particular we've got to be particularly careful in being willing to take the pieces apart and put them back together in different directions.

Theory and Law

Although not prompted at the time, Dr. Hershall discussed his ideas of theories and laws in the contexts of biology and physics. The key here as an interviewer was to prompt reflection as relating to his work.

H: I really don't pay much attention to what is a law versus a principle or so forth. You would have to find that in text books. But I think there a couple of key points. There are certain things that rules have been made over and over again, the observations. There is just no point in really questioning whether it is real or not. You know the second law of thermodynamics, from the biologist's point of view, or the three laws of thermodynamics are going to hold true. An electron is a concept that is so powerful that it has to be a real species as far as. . .because you can predict exactly. If you don't, if you lose an electron in a system, you've done something very wrong. Your theory is obviously wrong, which is something that biologists often don't look into or they forget about electrons and don't realize that there is an electron missing for a chemical reaction that occurred. So those are things we have experienced that you can use over and over and build and make very power predictions from. So that is what the laws basically are, observations you can use or count on as a foundation and you don't need to rejudge it. One example is that the speed of light is a constant. It is a very powerful idea and if you are a cosmologist, it actually is very useful to think the speed of light might change or be different from one edge of the universe to another. And that is what theoretical physicists do. For me, it doesn't make a blink of difference in the type of research I do. It is at a certain number that we can use very consistently. So that is where different disciplines come in.

S: Can you explain to me what a theory is in *your* work?

H: You know I don't really try to think through that much.

S: Do you use it interchangeably with hypothesis?

H: Yeah, I would think theory is more global. Theory should try to explain a large series of facts based on a few simple postulates. A hypothesis is one prediction that you would make one test out of. So one theory could lead to many hypotheses. One debate is if evolution is a theory or a fact. Is gravity a theory or a fact? So I got into this with some born-again Christians at a Boy Scout meeting where I couldn't hold my tongue much longer and I said, "Yes, gravity is also a theory and it's actually less well understood than evolution, even though there is no doubt that if you fall off a cliff you are going to hit the bottom. And you are not going to evolve in that time scale." So, that is where the definition of a theory gets to be more complex. For a mathematician, a theory has a set of very precise questions that reads to [unclear] such as the good ol' completeness theorem, the good ol' incompleteness theorem. You can never construct a theory that can explain everything for something like evolution, which is a very general and sometimes a vague theory when you start looking at specific groups of organisms as compared to the power and prediction of gravity. But when you try to resolve the underlying principles of gravity, it turns out to be much more difficult than to try to understand the principles that drive evolution.

H: . . .I would consider a theory as a way of rationalizing a phenomenon. It is extremely important for teaching. Because you have a bunch of disparate facts out there and what you are looking for is finding a common pattern or a way of explaining them. So if you have a theory, you explain a large number of them. So if you grasp this theory you can predict these facts and you can also make sense of why something occurs.

More on Theory, Law, and Change

S: How about change? Do theories and laws change?

H: Certainly. Theories in particular change because there are new facts that come. They can't figure out how to fit them; so you have to modify the theory or make the prediction and that comes back to the hypothesis being disproven. So if you make a hypothesis based on a theory, and the facts don't fit the hypothesis, you then have to come back and question the theory. Sometimes it is a simple formulation where you just missed one step and other times it means the whole thing is wrong or it is an approximation. That happens all the time in the field of ALS where I am. There are a lot more facts being discovered that people don't understand and trying to find a theory that would explain them and make the predictions. The catch is other groups would say you also have to go through this. . .you should measure that. . .and we don't have the technology to do that at the present point.

. . . .A law in principle should remain constant. So the second law of thermodynamics is one example, which in our world makes a lot of sense. To theoretical physicists. . .with a black hole, the concept of entropy at first don't seem to make sense. . ...but them people have been working through this and redefining the meaning of entropy and seeing how they can make it consistent, and somehow having insight into how the universe might work. And that is basically where laws are still theories that are well accepted, but every once in a while it is worth considering, is there a way around the law? Is there an exception for it?

Laws in Biological Sciences

S: Do biological sciences have laws the way. . .like the examples you have given for physics or chemistry?

H: Yeah, in fact I think there are more laws, at least from the way I look at it, than biologists believe, and they just haven't learned how to use the information that is available from chemistry and apply it to biology. We always think there is an enzyme that will catalyze something. We don't worry about the thermodynamics because we always assume ATP will come and supply all the energy you need. In fact when you go back and apply it, you can get great insight into the way biological systems work by applying chemical principles and chemical laws. They give you very profound insights into why things occur in the order they are. That is why I really love biochemistry.

Science Is. . . "You Day Dream"

Immediately after the above statements about laws and biology, Dr. Hershall remembers a story from his undergraduate days about learning mathematics. He relates this story to children's learning and then to how science is done. I am particularly intrigued by how he describes the distinction between how you *do* science versus being in the *profession* of science. What does he say about the role of argumentation as being a part of doing science or being in the profession of science? Can they really be separated?

H: I think the other point to consider, this was a point made to me by a physicist when I was an undergraduate. . .In the 1960s they developed the new math. So they got all the theoreticians together and they discussed, "How do we teach math? How are we really going to teach children about mathematics?" So they start with the simplest concepts and build forward. Start with sets and unions of sets. You know it takes a mathematician 100 pages to define the number 1. So all of us were subjected to these [expletive] sets and unions and intersections and nobody really understood math. It really put mathematics back. Children understand complexity. What they do is they see a complex set of facts and they play with random combinations until they find some combination that unifies the two. They are very good at filtering very complex information, finding patterns beneath it. Whether they are dealing with language…a young child can hear four or five different languages and associate them into different patterns very quickly. *So that basically is what science really is. You get deluged with a bunch of facts, you have to sit back, you don't worry about laws, theories, or principles, or anything. You daydream.* As I go through I sometimes find two different papers in the messy office and say, "Wait a minute. There is an interesting connection." That is largely what you are doing as a scientist. So what you are talking about with theories and principles and hypotheses is how I can convince my colleagues that I have thought through this well and it might be a physically meaningful principle. So basically what it comes down to is that science is a way of simplifying and expressing patterns and a way of testing whether or not those patterns make predictions in a way that other people can apply it and understand it. So that is what the real divergence is between how you do science versus what being in the profession of science is. *Doing science is playing. It is a lot of fun. The profession of it is convincing other people that you've really done something, that it is not an artifact.* That it's important and they ought to pay attention to what you've done even though you are not paying attention to what they have done.

S: Are there two different roles?

H: It is a difference in creativity versus marketing and establishing something as a fact. Artists can be extremely creative but if they are not somewhat savvy about the marketing they starve. When Elvis Presley committed suicide one [unclear] noted as a great career move. That's a little bit extreme, but it doesn't help you as a scientist.

Hypothesis, Prediction, and Proof: "You Can Only Prove Yourself Wrong"

Dr. Hershall discusses his ideas about the importance of hypothesis testing. From this excerpt, we also get a sense of his view about the tentative NOS, in that proof is not possible.

H: The concept of hypothesis is actually very important because you can never prove yourself right. You can only prove yourself wrong. That is something that people tend to forget because you have so much invested emotionally in what you are thinking about or in what you are doing. But you collect data and you can have an idea and make a prediction as to what it might be and that is what your hypothesis is, and you test that. If it doesn't work, you know something is wrong with your hypothesis. If it does work, uh…there still could be other ways to explain it and you try to go through those in as many ways as you want and can to try to disprove the hypothesis. Even then it is not finally proven.…So you are looking at a set of facts and say this is the case and this should follow, or this should happen. And then can I measure that or is there a way I can do something to test it? So it is nice when your theory is right and particularly can be very quantitative in parts of biochemistry. Sometimes you get really lucky and you can predict, based on numbers, we can calculate something, we can measure it, and it falls spot on. So that is nice, but that's not absolute proof that that *is* the way it happens. There could be different ways of getting there.

Tentativeness and Anomalies: "That Is Actually Where Real Progress Comes From...."

He immediately goes on to discuss how a scientist might determine one or more of those different ways. His enthusiasm came through as he talked about how science progresses through anomalies. He provides examples from different sciences whose complex variables lead to more anomalies.

H: It's when you do an experiment that you think is pretty obvious and you know the outcome and it doesn't turn out that way. You repeat it to make sure you didn't reverse the test tubes and it still comes out wrong. You do that over and over again. It is frustrating, uh...and a lot of people think well.... "How do you have the patience to do it?" *That is actually where real progress comes from because when you understand that you realize you weren't thinking about it very well and nature had a much better solution for the whole thing*. ...when you understand it, you have to look at from a different perspective and then you have true insight into the problem. *So I am much more encouraged by having an experiment that didn't work when I am sure that it isn't because of some stupid mistake or instrument artifact*. You have to do a lot of checking to make sure that is the case. That means I've got to go back and think and puzzle on it for a long time and find some more information, do more reading.

H: ...There are two ways to look at anomalies. One way is that it could be a consistent anomaly. In other words, you think it should go that way and it doesn't go that way, or it goes completely opposite and it does it in a reproducible way. That is very exciting. It could be that you do the experiment once and it goes this way, and you do the experiment again and it goes the other way, and you do it again and it goes a third way. Then you have a problem of reproducibility. You've got to figure out, uh..."is one of my instruments bad? Is one of my reagents bad? Am I forgetting to control something? What is the variable in this?" In other sciences, particularly social sciences or sometimes genetics, or environmental science where you have to take a statistical approach because there are too many possibilities, you can't control everything. Those are actually very difficult problems to try to understand and convince somebody else that what you are talking about is really important. An example would be global warming. Have our effects really made a major difference in the environment or are we looking for [unclear] and if you look at global changes over a large time scale, you are still only 1% of the variation that is known to occur. Then you run into the political implications of what that means. Do you shut down billions and billions of dollars of industry or are we worrying about something that isn't that major a problem?

Science and Art

One of the questions on the VNOS-Sci asks about the similarities and differences between science and art. A typical response from undergraduates, secondary students, and teachers describes artists as much more creative than scientists because an artist can do whatever he/she wants and call it art, whereas scientists have rules to follow (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002). This group of scientists tended to say that both scientists and artists are creative, but the difference comes from reproducibility (Schwartz & Lederman, 2008). Art must be unique. Science must be reproducible and come from the real world (empirical). Here Dr. Hershall discusses his views of science and art:

S: Can you tell me a bit more about the connection, similarities, and differences between science and art?

H: I think in art you don't have the connection to physical reality that is important. In art you are trying to stimulate the mind into new directions. In science, what you need to do is to explain some part of the physical world to make predictions that can be tested, that your creativity is giving you new insights into how things are connected and why they function in certain ways. In art you don't have that necessity. In fact, to be very creative you don't want it. You want to be nebulous and open ended and lead to new directions. So I think scientists enjoy art a lot, but they also have to have a very pragmatic aspect at the end of it. In some ways science is a blend of art and engineering, where in engineering you have to accomplish something that actually functions and it can be a very creative process, but there is a standard set of principles that you work through.

The Purpose of Science: Predictive Value and Economic Benefit

The science/art question often opens the door to discuss the purpose of science. While students often describe a humanistic purpose (better our lives; make the world a better place to live), this perspective was not consistently seen among the scientists in the sample. Although not directly connected to a targeted aspect of NOS, this discussion was interesting in that Dr. Hershall provided insight into his view of different fields of science: (e.g., medicine or physics).

S: Does the product of science have to have a function?

H: [nods his head]

S: What kind of function?

H: I think it has to have some kind of predictive value, to give you some insight into how things work. So you can do two types of science. You can go out and catalogue everything and end up with a notebook, or you can end up with an algorithm that will tell you basically how to generate the entire notebook. The formula is basically the underlying principles behind the organization. So the science is finding the underlying and organizing principle.

S: Do different types of science have different purposes?

H: Sure, that is one of the interesting things about leaving a medical school and coming to [university]. Just look at the biological sciences; if I asked a question of the medical school class and used a plant biological example, they would all go to the Dean and scream, "This is completely irrelevant." The idea that you might learn something from a plant that would apply biologically to medicine and it would be something you would want to quiz them on. . .So sure, in a medical school you have this disease orientation. At [university], one of our strengths is looking at health. There is no money in health. There is a lot of money to be made in disease. That is what medical schools focus on, and a lot of them are a lot richer than [university]. In physics, you can certainly split them into different areas. There are very practical materials physics and applications. There are others that verge on relevant philosophy which is basically theoretical physics. They try to make predictions about what the universe is . . ..[unclear].so I think the real difference in purpose comes down to what kind of economic benefit you get out of it. And that's what really drives what you would perceive as differences. Overall purpose still comes down to knowledge: Can you predict something? Can you derive an underlying principle?

Economics and Collaboration: "There Is a Real Revolution that Is Happening in Biology. . ."

In this next excerpt I was interested in finding out what motivates scientists. The conversation developed quickly from economics to the growing role of collaboration and the global community in biological sciences. Dr. Hershall uses physics research as a model of collaborative work: a model that he feels biologists are moving toward.

S: Do you think the economic benefit drives what the scientist chooses to study?

H: Sure, you need to stay funded in order to do your research.

S: Is that a personal gain though?

H: Yeah, it basically ensures you can have an academic position or you'd spend all, 90% of your time teaching. So being able to come up with a private goal to explain why your science is important in practicality is extremely important in being successful. . .I suppose another thing that is different in biology and physics is that in physics you assemble teams of up to 1000 scientists to accomplish one thing, to measure the . . . .you all work on the accelerator. As biologists, we've all been individuals. We all work on individual parts and the major change that is happening in biology in the last 10 years is starting to work in larger teams, the genome project for example. You can view biotech companies as simply a large physics experiment getting focused on developing one particular idea into a product or useful concept. So that is the real revolution that is happening in biology, larger systems and coordinating team work, pulling different disciplines together toward understanding a particular problem.

S: How has this changed your own work?

H: It is almost daily. You have to pay attention to the catalogues that come in and find out how the technology has changed. It changes so rapidly. I feel like I am still a student, a graduate student trying to learn all the different aspects that are involved. The other thing that is key for success in this is to travel and interact in meetings. It turns out that scientists are some of the most traveled people in the world because the meetings are so important to exchange information. . .and finding out what else is going on. In a large part in random contacts, you discover something you didn't know was going on for 5 or 6 years and it may change the way you think about it. The other part of it is just trying to find out what is really out there. So information technology is really driving a lot of development, web resources are usually important.

Science as Collaborative, Yet Socially and Culturally Sensitive

Dr. Hershall works with scientists from Germany, France, South America, and United States, among others. I asked him about the collaborations and how the various research programs fit together and how he works with the others.

H: We all have our own expertise. So we feed back to each other and then you have to kind of try to spend a lot of time figuring out what the other people are talking about. It is hugely important too because I cannot keep everything that I should know in my mind at once. Just talking to various people about a paper or something I've forgotten completely about. . .it's happened. . .and so that is what keeps bringing up the facts that you have to incorporate into your theory and make sure you have. . . .what really drives this is that you don't want to be wrong. You don't want to be embarrassed. Reputation is extremely important. That means you have to know all the facts that are out there, weigh them and try to make your own decision as to how much to weigh a particular fact. Sometimes you can't fit it in so you just hold them and say I don't understand this at this point. You have to be honest about it. . . .You can't be a perfectionist in this field. People who are either go into theoretical physics or become pathologists or they fail, because there is no perfect experiment. There is no perfect set of data.

We discussed the role of culture in the way scientists work, and the influence of that culture on his collaborations. Through his experiences with scientists all over the world, he had identified different working styles, purposes, and forms of justification. He also explains his view of how science can be a common ground across cultures.

S: Working with people from all over the world, do you see any differences based on culture in how science is done?

H: Sure. Very much so. Americans are extremely competitive and hardworking and driven, pushing at the latest technology. They follow trends and fashions. In fact if you don't follow the latest trends you get penalized in your grant reviews because you are doing something that is old and everybody knows it. In the European system it takes forever to get established and the probability of succeeding is . . . once you are there, you've got great freedom. You can work on things that interest you to a great extent but you don't have to be competitive and right at the cutting edge. I really like South American scientists because they can't afford to buy a box of reagents. They think about their experiments a lot more. My friends there are a lot more philosophical. At first I am uncomfortable listening to what they are talking about because it isn't real rigorous, but you have to sit and listen and suddenly the brilliance comes through, that they have sat back and gotten at the bigger picture. And the Japanese are a lot more difficult to understand in a lot of ways. A lot of them do get very focused toward whatever their major professor or director of the institute is focused on. They tend to work very hard to get a very high level of skill on some particular problem. But often times they are looking at one tree in the forest and have no idea of what the forest looks like. But there are exceptions and they are very important. They also have a different philosophy in how they make their judgments in what science is.

S: What do you mean?

H: I don't really know how to explain that, but the thought process is different in many ways. You need to be careful when you are judging your science . . . So a Japanese professor, and I've made this mistake, you never say "no" to them. That is very rude, culturally. So people will argue around something and not tell you [that] you are wrong or the idea is wrong, but kind of lead you to this impression. It is very easy to overlook, in part because of the language difference.

S: Do you see culture as influencing science? Do you see science as being universal? Can it be both?

H: Absolutely. The whole idea of science is being able to convince someone else that the underlying principles such as general applicability and basis in reality, and so that is what everybody agrees on. . . *That is the beauty of dealing with different cultures. Uh. . . they will take what you say and interpret it slightly differently. That leads to new insights and [goes] in different directions*. It will reveal different aspects of it. That is where the communication is really important. I think [unclear] globalization. In fact I deal with people all over the world. That is one of the great benefits of working in this place. . . *It is also that you've got a group of nerds that you can go wherever in the world and you've got a common thing you can talk about*. Even though we are fighting a war in Iraq and the Italians and French are all furious at us, we can sidestep these issues and still have a lot to talk about and common ground to discuss things.

The Luxury of Time: "...Realizing the Complexity of What I Assumed to be Facts..."

Toward the end of our conversation, I asked Dr. Hershall to reflect on how he thinks his ideas of science have changed through his career. I was interested in learning how he thought as a science student versus the experienced and successful scientist he had become. He shares a story about "truth" and everyday influences on how people view science.

H: My view has changed a lot from when I started out. I couldn't believe in Kuhnsian paradigm shifts.
S: When you first started.
H: Yeah. Well of course there is truth in knowledge, you know. Everybody knows what is right and wrong and it's absolutely true.
S: That is a very interesting statement. As a graduate student you held these views?
H: No, more as an undergrad. There is this story of a guy who goes looking for truth. He travels up the Congo and is told that if he goes further up, past the mountains, past the headwaters, in a cave there exists truth and you can ask her anything. So this guy goes through all these horrible trials of survival. He finally climbs up to the cave and looks and sees this very old woman sitting there. He asks, "I've traveled a long way in search of truth. Are you truth?" And she says, "Yes, I am." And he says, "I expected Truth to be this beautiful wonderful thing, and no offense, but you are old, haggard, and very worn." She says, "Yes, I know. Please don't tell anybody."
H: The other thing is watch the news. Everything is reduced to 5-s sound bites. What you do to establish this is find the two most extreme views and you hype those extreme views. So you present only a few of the facts as perceived by the most extreme people and take polls to turn people's opinion around. It is the most anti-scientific destructive process I can imagine. So much of it is superficial and not presented within a framework for judging it. And you are not given all the facts...It is like when Richard Feynman won the Nobel Prize and a reporter asked him, "So can you describe in two to three lines why you won the Nobel Prize?" His response was, "If I could tell you in two to three lines, I wouldn't have won the Nobel Prize. It wouldn't have been worth a Nobel Prize."

He came to realize through his career that science evolves. His recollection and examples of revolutionary changes in science are also couched within how he views the strength of scientists' opinions and how those opinions impact in what direction and how science progresses. His statement implicitly revisits the "puzzle perspective" where there are different ways to put the pieces together:

S: So what turned you around from being anti-Kuhn?

H: It was basically realizing the complexity of what I assumed to be facts, was finding out the basis for them was not all well understood. It was a large part, my personality. It takes accumulating more and more knowledge about where things came from to understand the history and also watching the evolution of science and seeing new facts that at the time you had no clue as to what their significance was, and seeing how much of a revolution is really going on. You can see that with geology and plate tectonics, that in a few years went from a silly idea to well. . . Wagner's original idea really didn't go far enough, so he is wrong now. Uh. . .or physics where you think of general relativity and Einstein theory was well established. You watch now the cosmology and constant debates are about whether we are missing a fifth force called dark matter; or is it a matter of the speed of light varying across the universe? So it is basically making judgments and understanding that a lot of people have invested a lot into certain theories and there are certain positions where they make their opinions very well known. That, for a while, drives a lot of science. Everybody is trying to grasp different sets of facts and put them together in different ways. So there is going to be diversity of opinions. People will judge different evidence in different ways. Different opinions are very strong in figuring out how to test things.

Experiment, Validity, and "The Problem with String Theory. . ."

In our discussion of experiments, Dr. Hershall explained that he views an experiment as a procedure to find cause and effect relationships. He gave examples from his work:

H: Most of what I do is try to understand cause and effect relationships. What causes the nitric tyrosine in animals? Can I give them a drug to block it and does it now have an effect on the disease process? Eventually I hope to test it in humans, but that is no longer an experiment. It is a clinical trial and I can't control the variables.

He discussed the distinction between observational studies and experimental studies by giving several examples from medicine and relating them to what he does in laboratory work. He recognized the strengths of both types of studies, but, as seen below, he struggled with comparing their validity. I prompted him to expand the discussion to other types of sciences because I wanted to know more about his ideas of "scientific" and "validity," as these relate to his view of the empirical NOS.

S: Let's go back to comparing fields of science. . .field ecology or astronomy or something else where you can't do manipulative experiments, or something else in molecular biology. Can you compare the validity of the claims made in those fields?

H: You know I don't know how to answer that because it is so broad in so many different ways. The answer is in astronomy for example, yes you make observations, but can you predict them from underlying theory? And so what it really comes down to is that you can do experiments in astronomy where you make predictions and you search for a particular type of phenomenon and that gives you some more certainty that what you predict will happen. It is useful, you've got a set of rules, things that will happen. You ask, "Does it happen and can you find examples?" Then you have to use statistics to decide whether or not it happened by chance or is this more consistent with there being a relationship. Are relationships driving it or is it pure chance? That's fine. So the validity, again, you never prove validity. You invalidate things. I guess that is where I am having trouble, struggling with this. How would you invalidate certain studies? Is there an experiment you can do to disprove something? *If there is not an experiment you can do, then what you have is tautology, and it is not terribly useful*. There has to be some defining experiment that says this is wrong, this is a lower bound of how this would work.

S: Can you think of an example of where there is not?

H: Where you can't disprove something?

S: Yeah.

H: Well, for example, string theory. Bottom line is that it potentially has the ability to explain, be the theory of everything. But so far no one can come up with a single experiment to test whether it is real or if the generalized appeal is real. So you can explain the facts that are here, but can you explain something. . .a new observation? Do you make a prediction from this theory that no one has thought of before that you can test? Or can you do an experiment where you can actually isolate a string and the calculations indicate the accelerator would have to be larger than the known universe, which is beyond the realm of testing? So is it worth doing string theory? Sure, it is a very hot field, but the bottom line is that if it is going to hold up, someone has to figure out a way to test it and make predictions you can't get from other theories.

S: So is it science?

H: It is science in that it is a developmental tool I guess. You have an underlying theory and framework that you are expanding, and you are explaining facts. *The problem with string theory is that it hasn't predicted anything in a way that you couldn't explain by some other phenomenon*. So it is not a theory of everything at this point. It is a theory that explains known facts. It is just it hasn't explained, made a prediction you could test and other theories would not have worked. So, is it science? That's probably putting too harsh a judgment on it because certainly you need to develop theories and give them time to evolve and see where they are going to go.

S: How does that differ from mathematics?

H: It is going to be really hard to distinguish the two. But basically mathematics is the underpinnings for the other sciences because basically it allows you to make predictions of physical phenomena and model it. The difference with mathematics is that you shouldn't try to constrain yourself to try to explain

> physical phenomena. Largely you are making conjectures. Conjectures in a way are hypotheses. You play with something for a while and it seems to make sense, and then you have to figure out from an accepted set of postulates how to prove that conjecture being true. That is how it has taken up to 400 years to prove some conjectures. So I think the difference between mathematics and science is that mathematics does not have to have a physical reality or prediction that you would test.

Dr. Hershall was expressive, articulate, and provided a clear picture of his views about science. I encourage the reader to revisit these last comments about string theory and mathematics after reading about Dr. Ross, as he also discussed these concepts through colorful examples and description.

Dr. Ross: A Discussion of Black Holes and Astro-exotica

Dr. Ross was recommended to me by a colleague as someone who might be interested and interesting for the study. I contacted Dr. Ross because he was a theoretical physicist and would provide a sharp contrast, as far as research area goes, to many of the other participants. When I contacted him, he replied quickly and affirmatively that he would participate. I sent him the two questionnaires, and he diligently responded within a couple of weeks. When I contacted him to arrange an interview, my intention was to speak with him over the telephone, as his academic position was in another state. However, he offered to meet me in person. He was traveling to my location over his summer vacation to visit some friends, and wanted to meet me. When the time came, I drove out into the foothills to the beautiful log home of his friends. Dr. Ross and I sat down at the large wooden table in the country kitchen and had a 2-h conversation over coffee. What a treat and an honor that he shared his vacation time with me. That is indicative of the passion and dedication Dr. Ross has for science, his work, and for sharing his work with others.

Dr. Ross is a male, approximately 55 years old. His area is theoretical physics. He earned a bachelor's degree in engineering and a PhD in theoretical physics. He acknowledged that his background in engineering likely influences his views about science. At the time of the interview, he had 32 years' experience in teaching and research in academia. He was a full professor at a large research university in the United States. He has a research group with four graduate students, two postdoctoral students, and several undergraduates. One undergraduate was 14 years old at the time of the interview, and she entered the university at age 12. He described the student as "unusual." He said, "People who are unusual in the way she is unusual, get attracted to physics." During our interview, I got a better sense of what he meant:

R [Ross]: *My field is called gravity.* Einstein's theory of general relativity is a theory of gravity. It is a mathematically fairly difficult theory and so working with it is interesting. Einstein's theory and the field of gravity have to do with black holes, the nature of the universe, expanding universe, gravitational waves. Those are the content of astrophysics that we deal with. In gravity research also there is a great deal of mathematics that isn't particularly related to astrophysics. Until the mid 1960s or so, it wasn't called gravity research at that time, it was called general relativity, focused on such archaic mathematical things that it was kind of in the outskirts of physics. It wasn't in the mainstream. With the discovery of quasars and subsequently the discovery of other astrophysical exotica, it was realized that there are occurrences in the universe where Einstein's theory is needed. Newton's theory is superb approximation that works for most of astrophysics and almost all of engineering, but Einstein's theory is needed. As more data have come we've learned that the universe is stranger and stranger than we realized, and Einstein's theory is more and more important. So the field has grown and become more astrophysical, more real rather than a kind of museum curio.

R: . . .In the last 10 years or more there has been a kind of synthesis of what we do, general relativity, crude space-time, gravity, particle physics, and string theory could be thought of as what most of us would think of as another field that is closely related. That is the general field I am in. It is a wonderful community. It used to be small. It has grown. . . .My particular sub sub sub field. . .is rather astrophysical but not related to data. *What I do is really applied mathematics with the motivation of gravity*. For the last couple of years I have been particularly focused on one very very narrow, but rather important problem. The world is spending billions of dollars, I mean that literally, to develop hardware to detect gravitational waves from violent astrophysical events. LIGO is now up and running. It is a dual instrument. It is a 400 million dollar project and they are looking for a 200 million dollar upgrade. They will likely with the upgrade see gravitational waves. A much bigger project that almost certainly will be successful is LISA (lasar interferometer space antennae) which may launch in 2010. That will afford different frequency gravitational waves, some different kinds of events. The most exciting thing that these hardware can detect is the gravitational wave burst from what seems to many of us the most exciting thing that can happen in astrophysics. Two black holes are going around each other. As they go around each other they give off gravitational waves. As those gravitational waves carry off energy, the two black holes move closer and closer until they create very strong gravitational waves, excuse me, gravitational wave field on each other, and so you get this incredible distortion of space-time. When they get close enough they merge into one final black hole. One black hole plus one black hole gives you one black hole. It is like piles of dirt. In that process there will be a phenomenal burst of gravitational radiation. That is the primary goal of LISA, to see the merging of the black holes. These would be super massive black holes that result from the collision of galaxies. You know galaxies collide. We believe many, if not most, if not all, galaxies have super massive black holes at their core. So when the galaxies collide, these two super black holes are going to find each other in the strong gravitational field and dance around each other. There is some question about whether the merger can happen within the age of the universe. But for some cases particularly with close encounters of black holes in the initial collision, LISA will definitely detect it. This will be such a strong signal. The noise will be so high that they will be able to say very accurate things about it.

R: In such work, as you know, you want to compare the measurements with the predictions of the theory. We can't predict. We have the theory, Einstein's theory. And it is a relatively simple clean system. Black holes have almost no characteristics. They have their masses and they have their spin. There is nothing more you can say about them. Simple creatures. So why not compute gravitational waves coming out? They can't be computed. The way we formulate Einstein's theory for computation and the state of the computers that are available, even the most powerful computers in the world can't do this calculation. So there was an injection of 15 million dollars in the early 1990s to a consortium of 10 universities to compute the gravitational waves that would emerge from this kind of event. It was a disastrous failure. The only thing coming out of the project was an understanding of what wouldn't work. *So what I've been working on is approximation, mostly physics. Physics is an approximation.* So I'm looking for the right kind of approximation to get useful incomplete answers while we wait. The wait will be 10 years or more before we get computer hardware sufficient for us to do this right, just for computing it. I've been very very successful in some of this. I've moved on to another kind of approximation. It's fascinating but difficult. *So I do applied mathematics with this motivation, to find a tricky way of solving this very difficult set of partial differential equations. It is not that we don't know the physics. It is just that we don't know how to get out a useful answer. So that is what I do.*

S: How will you know when you have a useful answer?

R [Ross]: Well it is mathematics so there won't be any question about it. Right now most of the community writes a computer code.....takes you forward in space-time. The problem is those computer codes crash. So how do we know when we have the correct answer? We have the correct theory that is going into the mathematics. If we get the computer code to run, it's easy to check to see if you have the correct answer. What you do is you change some of the computing details without changing the nature of the problem. If the answer if consistent, there is well-worked out protocol for seeing there is nothing wrong with your computing. So that won't be a problem. Just getting an answer out is the problem.

... About 8 or 9 years ago I worked out an idea in about a day that turned out to be one of these gems. We run everything out of it that could be....By looking at the very last moment of the spiral, you could make

> a simplification. That simplification agreed with what supercomputers could do at that time. Where they took years and billions of dollars, we could do on a work station in seconds. That was one of those wonderful triumphs that don't come along very often.

Science and Art: "In Science, Truth May Be Arguable, But Nonsense Is Unambiguous"

We reviewed his responses to the VNOS-Sci and VOSI-Sci questions. These questions prompted additional thoughts and examples that both participants shared. Dr. Ross had thought about the questions since he wrote his responses, and was very willing to discuss them further. In the question about the differences between science and art, he had written, "In science, truth may be arguable, but nonsense is unambiguous." I specifically asked him about that response, and he shared his ideas as they relate to theoretical physics.

R: That's right. I will stand by that. There are certainly elements of taste. There are elements of subjectivity. There are elements of fashion. There are those elements in physics too, especially recently with cutting edge theoretical physics. You can string along lots of ideas. Some of the ideas can be appealing because of the aesthetic elements. Certainly general relativity, Einstein was largely motivated by aesthetic considerations. The aesthetics aren't exactly the same as they are in art, but the aesthetics are more the same than they are different. Yet one can recognize something that is total crap. If something that is mathematically inconsistent or if something is inconsistent with a great wealth of data that is known about the physical world, you just don't give it any further consideration. It is wrong. So that really is the difference. It is difficult to really pin down the way good science and art are different, except of course, the mathematical content could be brought in, the restrictive strictures of mathematical consistency. But you can say there is bad science, but I don't think you could say there is bad art. Right? Look at Grandma Moses in the Renaissance. Her art would have been laughed at as the scribblings of a sick child. Yet another group of people find that attractive. . . . . .

S: The idea that the "truth may be arguable," where do the arguments come from?

R: The arguments come from the impression of data. Did I mention the Hubble Constant as an example? By definition if you are at the cutting edge of science, the answer isn't clear. It is almost always true. . .maybe always true. . .that if you are doing something brand new, cutting edge science, general relativity replacing the paradigms of Newtonian physics, plate tectonics when it first came, extinction of the dinosaurs, DNA, etc. *At least for some time, the new theory is interesting, but it is controversial. You can take all the data at hand and you can say yes it is good or not good. It is controversial. Ego will be involved. I think ego is a great thing. Without it there wouldn't be progress.* In that sense, there can be controversy about what is good and what is bad science. Ultimately, most. . .ultimately the establishment will come strongly to favor one side over the other.

Controversy and Data: The Subjective and Empirical Nature of Science

His comment raised the opportunity to explore ideas of controversy and how they might be resolved. Dr. Ross explained his views and gave examples of competing theories and how they came to resolution. I was especially interested in his ideas about cutting edge theoretical physics and the role of data.

S: How do they [the establishment] reach that point [of favoring one side over another]?

R: They reach that point by virtue of the fact that the controversy itself draws a great deal of attention. That brings in lots of more careful thought. It brings in lots more data and the accumulation of the data and the refinements of the argument caused by this extra focus mean that it becomes harder and harder to maintain. Certain people, because of the controversy, questions will be asked. *It will be realized that data exist or arguments exist which make it very difficult to maintain one side of this argument. A classical example is the big bang picture*. The big bang is not a specific picture, but it is a general structure for understanding the nature of the universe. . .that versus the steady state universe which was considered up to possibly the 1960s or so. The same data were available. Smart people on both sides, but more and more data came in, cosmic background information in particular, that made it look just so implausible that it was steady state.

String Theory: "They May Have It Right, But How Will We Ever Know?"

Dr. Ross described how controversies may be resolved. String theory is a controversial area of research, and he discusses the unique aspect of string theory as nonempirical:

> There is a period during which there is controversy. Here is an interesting question. *In the cutting edge of modern theoretical physics, it is getting more and more difficult to get data. You can't do the experiment*. String theory for example and particle physics beyond the standard model, require energies that are just not available in terrestrial machines. Cosmic rays bring in super-high-energy particles which might provide some data. But it used to be, when there was a controversy, you'd design an experiment. We've gotten as far as we can with those experiments. It may be that now these controversies last longer for two reasons. One is that the data are not. . .the data will be very difficult or in principle impossible to get: after all if some conditions only existed at the beginning of the universe, you just

> can't duplicate that. Secondly the mathematics is so difficult that it may be extraordinarily difficult or maybe impossible to use mathematical restrictions, mathematical considerations themselves to nail down sufficiently the field of possibilities. Right now theoretical physics is in a strange state. String theory is like nothing else seen before. It has become a sort of self referential subgroup of physics, to no longer really interact with the rest of the physics community. *They may have it right, but how will we ever know?* . . .They [string theorists] do form their own subcommunity. Some people have their foot in two fields or one toe in the rest of the community. So this is an interesting new development. I don't think it could have existed 20 years ago, but it might be more characteristic of the future. I'm not really knowledgeable about the other frontiers of science. But in genetics now I think that the experiments are becoming so difficult that controversies are lasting significant times. I don't think we will get to the point in the near future where the controversies will persist forever. There always will be ways to get more data.

Models: Motivating Questions and Making Meaning of Data

Dr. Ross discussed models consistently through our conversation. He seemed to tie nearly every aspect of NOS to models and modeling. His written response on the VNOS-Sci was:

> Without scientific models, observation would amount to cataloging data. The models help organize the data. Much more important, the models motivate the questions to be asked of the data, and thereby determine what data are going to be taken.

During the interview, he provided examples of how models influence early stages of investigations and develop to become more robust and mathematically predictive. In the excerpt below, Dr. Ross describes model development from indirect data. In his view, multiple conclusions are possible from indirect data that produce models with multiple parameters.

S: Let's talk about the dinosaur extinction question you mentioned. You state the data are sketchy and connections to the data are indirect. Can you explain what you mean by an indirect connection?

R: Almost any kind of a scientific argument is a house of cards. It is a structure built up by layers, connecting the data with conclusions. It is essentially impossible, maybe that is a slight overstatement, but it is essentially impossible to separate the use of data to prove or disprove a theory from a model. Basically, when data comes in, you are proving or disproving a model of how this happened. Well, when you have very sketchy data and you have a model which has adjustable parameters, a model which is not just a monolithic model that is cut and dry, but where there is something vague enough so that a lot of adjustments can be done, this is the general idea of the big bang. . .then it can be possible to maintain different theories.

R: Gamma ray bursts come to mind. It is something for which we don't have the answer. The most interesting recent new discovery in astrophysics is gamma ray

> bursts, bursts of gamma rays which are like x-rays but are higher energy. What are those things? We don't get to fly out to the edges of the universe and hover around these things and see what is happening. What do we get? Well we get burst of gamma rays on our satellite detectors. Where are they coming from? Well, somewhere out there. What direction are they coming from? Well, the early gamma ray detectors would show a burst of gamma rays coming from that part of the sky. They weren't highly directional. They would say look generally over there. Well, what you might consider a pretty definite direction in human terms, but if you look at the number of stars and galaxies and stuff out there, they are uncountable. You needed a much better angle of resolution. What would be better? What would happen? Well, someone would notice that at about the time of the origin of the burst that happened over there, that there was something optical that happened that was interesting in the same galaxy, very indirect. Was it the same thing? Who knows? Something happens which may or may not have been connected with the gamma ray bursts, that is indirect evidence that can support your hypothesis or not, depending on how you want to interpret it. . . .*There is a lot of data and it doesn't mean anything until you have a model*. If you have all these data and lots of satellites taking all these data, it doesn't tell you what to look for. It just tells you whether a model you have is plausible or not. It is all indirect.

Explaining Data: It's a Matter of Perspective, "Of Course"

S: So you have the data and you have the model. Or do you have the data and you develop the model? Or you have the model first and get the data?

R: Interactive. Let me tell you an anecdote which is kind of funny and tells you something about scientists. This is about [name] who was the originator of the steady state theory. Someone came up to him at the institute he worked at and said, "Sir, I don't understand. I just discovered a binary pair of stars, that's two stars going around each other, and the more massive star. . .they are both variable stars. Variable stars oscillate in brightness—dim-bright-dim-bright. Ok. And he said, the more massive of the two stars is changing its period more quickly. And [name] said, "Of course." And he explained why that would be. An hour later the guy came back and said, "Wait a minute, I screwed up the data recording. It is the less massive star that oscillates its period more quickly." And [name] said, "Of course" and explained.

Models: From Exploration to Mathematical and Predictive

All the scientists in the study discussed the role of models and modeling in their work. Some scientists in the whole sample described models as products of their investigations; some described them as integral to the processes they used to explore complex phenomena. Some identified how they used models as both process and product. Most of the scientists discussed the role of models in making and testing predictions. These discussions were always related to the purpose of science. Dr. Hershall described the predictive power of science. Dr. Ross also emphasized the predictive power of science, while, as seen below, he clearly connects mathematics to prediction. Dr. Ross was unique in his explanation of mathematical models. In his view, the goal of studying galaxies is to develop mathematical models that are predictive. The process of developing the models involves data gathering, interpretation, and model refinement.

R: So when you get data, you start on a path of figuring out what might be responsible for this. You get all the information that you can and you try to think of what might work, what is unlikely, etc. *And the mature final act in this play is to have a definitive mathematical model so that you can make rather specific and definitive predictions of what will come out.* But the early stages are an exploration. So suppose someone came to me and said early on,. . .and I've seen this play out with gamma ray bursts. . .they say, we are seeing these gamma ray bursts, much more frequent and powerful than we previously thought. My first thought would be it is a nuclear process. Why? Because gamma rays. . .why do we see only gamma rays? Gamma rays are relatively hard to detect. Why aren't we seeing stronger x-ray sources. . .what particular processes produce gamma rays more than anything else? Nuclear processes. Then someone would say, on the other hand, we are seeing the following. And it might be evidence that makes it quite difficult to maintain that it is nuclear processes. I would then try to think about whether these things are in the galaxy. So I would say, "When you see these things, are they aligned with the plane of galaxies?" Someone would bring forth data. Maybe there would be 30 of these events in the data gathering. You'd look at them and try to figure out whether they favor the plane of the galaxy. If all of these things were incredibly well aligned with the plane of the galaxy, there wouldn't be any question. If these things were beautifully isotropic over the entire sky, you'd say, "Oh, it doesn't look good for the plane of the galaxy." But, you know, the way it goes is that it is always somewhere in the middle. The same people can take a look at those same 20 or 30 data points and say, "Oh, yes, there is definitely a tendency for them to be in the galaxy." And another person will take a look and say, "Oh no, there is no signal for them to be in the galaxy." *That informs model building, and the model building informs what to look at, what questions to ask of the data. Then more data comes in and the whole process gets refined and so on and so forth.*

S: Until eventually what happens?

R: Until eventually you cannot maintain certain models and perhaps new possibilities develop for alternative models or you focus on one model and the questions change to the details of that model.

A Definitive Model and Anomaly: "Now There is Something New"

As with all the participants, I asked about the role of anomalous data in their work. As seen with Dr. Hershall, responses typically described science progressing through anomalies. Dr. Ross gave an example from his work, while maintaining that the definitiveness of the mathematical model influences how an anomaly is recognized. Here, we gain insight into how Dr. Ross connects the empirical NOS, mathematical models, and change:

S: So let's say you have an established model, this gets at the anomaly question. . .All of sudden you notice an inconsistency.

R: This happened just recently.

S: How do you recognize it and what do you do?

R: It depends. If the model is a really specific definitive mathematically definitive model, because if it is a vague model, or idea. . .because right now our ideas of gamma rays are vague enough so that an anomaly. . .I don't even know what it would mean. . .no particular one observation would be too disturbing. Let's talk about something else, some example I think is close to what you are talking about. The expansion of the universe. There is a pretty good model for the expansion of the universe, Einstein's theory as the description of gravity. Gravity as the primary driving force in the expansion of the universe. Suppose you find an anomaly. They did. They found an anomaly. The anomaly was evidence of various types that the expansion of the universe isn't slowing down as much as it should be. And in effect the universe is accelerating more than it should be. This has shown up in several new forms of cosmological data. And the evidence is becoming undeniable. *Now, the way it works is when an anomaly develops, initially the data is vague and some people can choose. . . .certainty in data. . .no problem. Others will say, "Oh, here is an anomaly,"* *and a chance to make up new theories and models*. So there will be a split. People will see opportunities to do work on both sides. In the case of the acceleration of the universe model, that lasted for 3 or 4 years. We happen to be in a golden age of cosmology where data are coming in very fast. And the data very quickly made it clear that you could not ignore the signal of dis-acceleration. And we are now in this very very interesting period of saying, "What is going on?" The old model, the big bang, said okay; but the standard model, Einstein's relativity, a universe that is full of stuff that is more or less like stuff we know although the dark matter, the missing matter, has been controversial. It's okay. It just means we can't quite figure out what it is. But now there is something new. And it is pretty well accepted. As recent as two years ago I think there was some excitement: people were saying, "It's data. You know how data are." But now in the past six months or year, people are saying, "Yeah, it's a problem." So what do they do now?

S: What turned it around?

R: The mass of data and the consistency of data. It has just really been pinned down too well. And so people are looking for experimenting with what ideas can fit with this. It is relatively simple mathematics. In fact Einstein kind of gave it to us at the beginning as one of the options of his theory. [Explains a mathematical term.] The name is *dark energy*. It is mathematics. They are trying to understand something reasonable to explain how 99% of the stuff in the universe.....how that can be so weird. That is where we are now.

Science and Mathematics

Given that Dr. Ross described his work as applied mathematics, I was curious as to his thoughts on the difference between science and mathematics. He once again brought up string theory as an area that blurs the lines between the two disciplines:

S: What do you see as differences and similarities in science and mathematics?
R: In mathematics you get to make up your own rules of the game. In science you play a game in which the rules are given to you.
S: Who gives you the rules in science?
R: The physical universe
S: Do you ever see a blend between science and mathematics in your work?
R: Oh yes, and sometimes it is not clear what you are doing. String theory is the best example. Sometimes the mathematics itself becomes the driving force, the beauty of the mathematics. String theory is much more mathematics at present than it is physics. They hardly ever talk about, they never talk about data. They are looking for mathematical consistency in patterns of symmetry of the theory. There are so many problems to solve before they can relate it to actual measurement that they sometimes don't even think about relating it to measurement. To me my love is applied mathematics. Being tricky and devious, using mathematical tricks to get answers out of the physical theory. But I am always interested in getting an answer out of the, well not always, sometimes I am interested in the mathematics itself. One of the things that characterizes physics is this enormous reliance on the definitiveness of mathematics. *The clearest distinction I can make is that in mathematics, in mathematical research, there is no external motivation*. You are fascinated by the mathematics in and of itself.

Creativity, Epiphany, and Luck: Making Sense Out of a Nonsensical Situation

Several times during the interview, Dr. Ross got even more animated in his descriptions. One of those times was when talking about his experiences with epiphanies and luck. The honesty with which he portrays his success in science reveals how he has changed through his career. His early successes he attributes to luck, and his later successes he attributes to creativity and openness.

R: Ego drives you to be creative. Science would be really boring if everybody just sat back and were truly logical and dispassionate about it. Creativity....wow...well I have funny feelings about creativity in science because there are these nonsensical statements that creative work is always done when people are young. I was very uncreative when I was young. I was proficient, but I wasn't creative. I am feeling much more creative now. I had to develop a background of tools, enough of a background so that I didn't have to think about the tools and I could think more about the more important questions with the tools operating in the background. So I didn't worry about them. So I think creativity can be funny that way. For me I needed to build up the clinical experience so I didn't worry about the small stuff, and I could be creative with the bigger ideas.

R: *Let me tell you something interesting though, in my career I think I've only had maybe three epiphanies where I saw through something so clearly that a whole messy impossible situation all of a sudden became crystal clear and obvious, and everything made sense. Whereas nothing made sense. . .suddenly everything made sense*. This was never done with paper in front of me. It was always done sitting back and having instant insight. Once it happened in the middle of the night. I woke up and this was about a Nobel Prize winner had been doing something wrong for over 10 years. It was clear that there was some mathematical problem and I woke up in the middle of the night. It was crystal clear to me. I went to my desk and did a 5-min calculation. It was not something crucially important. . .well it made him look funny but it was so clear at that point.

S: This happened three times to you?

R: Three times. . .seeing it for the first time was this wonderful insight that took an impossible situation. . . . .this one key idea made everything make absolute sense. The others were not as important but they were beautiful examples of making sense out of a nonsensical situation.

R: There is such luck in research. For my thesis I solved a fundamental problem in black hole physics. Now I am recognized for solving it. This was my PhD thesis. And along the way, I'm not a modest person. I'm honest. I was so lucky. In my work I stumbled across all these things that were important. You see [shows me his coffee cup that has equations on it] this is called a ["Ross"] Tail, which amuses my wife to a great extent. . *.I was a failure as a graduate student and suddenly became a hero. . . .luck!* If I had not done that particular computation and made that particular graph. . . . .my whole life hinged on that one piece of luck.

Comparing Types of Sciences: "I Don't Use Data Because I Know the Theory"

I was really curious as to how Dr. Ross thought about data and how he compared what he did with other ways of doing science. It was intriguing to hear him discuss himself as an applied mathematician as well as a scientist.

S: You mentioned several times in here [surveys] that you don't use actual data.

R: I have a little bit.

S: So how does your approach differ from something like a field ecologist or a molecular biologist in the type of approach you use?

R: I'm working with a theory….that is an excellent question. It's the nature of what question we are investigating…they are trying to figure out what theory or model applies. I know what model and theory applies but other people can't get the answer, they can't ream the answer out of the mathematics. As I said several times, what I really do is applied mathematics. If I ever considered another career, it would be applied mathematics. I love that sense of being tricky and clever. So I don't use data because I know the theory.

S: So those sciences that use data, do you say they are…I don't want to put words into your mouth here…are they theory development, model development?

R: Model development, yeah. …well there is not a clear word. Wringing answers out of the mathematics, checking models maybe, or developing applied mathematical techniques for using the models. That is what I do.

Empirical data and argument are conventions by which scientific claims are judged and accepted. How is it, then, that scientific claims are judged if they are based on mathematics? Dr. Ross explains the difference between accepting the mathematics and accepting the idea that emerges from the mathematics.

S: What are the conventions of acceptance of your type of work?

R: It is quite easy because everyone can check, with the exception of enormous computer codes, anyone can check the details. The acceptance of that kind of work is broad. The acceptance of the idea is something else. For instance, in this work with periodic approximation the idea of figuring out the slow "inspiral" by solving the mathematics of the "non inspira," people can argue about the usefulness of the solution and about many aspects of that. Because I am not giving them an answer. I am proposing a method for getting an answer.

R: Also…initially and typically, one works with simplified models. Instead of using this method for Einstein's equations, I first used a model of Einstein's equations with lots of complexity thrown out. I could demonstrate that certain things worked that might sound pointless, but the very idea of getting an answer out of these problems, most of us would say it is mathematically ill-posed. Without the complexity of Einstein's equations, there are features of this mathematics that are contrary to the usual rules of thumb. In my initial view, I initially thought this was bad because we were violating the usual rules of thumb about what constitutes a well-posed mathematical problem. So I had a physical vision that must be okay. *Then I came to the understanding that it was okay to violate the usual rules because those rules were not absolute rules about what works and what doesn't. They are rules about what will guarantee something will work, but they are not rules that say if you do it another way it won't work*. And I understand that much better now. So I checked a lot of these things out with really simple models and tried to publish it. And I ran into trouble. Because people would say [unclear]…I ran into some problems. I almost never have trouble getting stuff published.

S: Do you consider there are other fields that don't use the same conventions?

R: Medicine….I've published in other fields. I love to do eclectic stuff and go into a field I know nothing about and use my abilities in applied mathematics to do other stuff. So I've published papers I couldn't read. I mean, I knew my part, but there are other fields, especially in medical research, they put people's names who have not really contributed or in some cases they may not even be aware of the existence of the paper. So it is politically motivated. In my kind of work this doesn't happen. It tends to happen because of the need for huge collaborations to do some huge experiments. Physics is a big field.

Discussion and Implications

From the interviews we glimpse an insider's perspective of how two scientists, from very different science communities, view their world of science. The contextualized nature of their views is noteworthy. However, as discussed in reaction to all the scientists in the study, the contextualized views are not based on discipline or likely even subdiscipline (Schwartz & Lederman, 2008). The context is of a smaller grain size—to the level of individual scientist. Each experiences science and his community in a unique way. The other scientists in the full study were equally as articulate and demonstrated a variety of NOS views, but none of which could be characterized as discipline-specific. When asked to describe his/her views, the scientist may first hesitate because the question seems so strange. "What is science?" It is an easy question, but it can be difficult to put ideas into words. Dr. Hershall and Dr. Ross agree that scientists do not think about these types of questions often or as they do their research. They both also agreed that students should learn about NOS features such as the empirical basis, tentativeness, and subjectivity. The two scientists presented here may not use these words, but the ideas are there.

We learn from these cases that scientists have unique styles and ways of expressing their work. Educators can use "*what scientists say"* (Schwartz & Lederman, 2008) to promote discussion among students about contemporary science practices. They can relate those practices and the ideas of scientists to students' experiences with science inquiry, and in doing so, explicitly guide students to reflect upon relevant NOS aspects. For example, both Dr. Hershall and Dr. Ross discussed how anomalies in data lead to excitement and progress. How are anomalies identified? The scientists have expectations and a theoretical basis or model that guide the data collection and analysis. When they find something that does not fit those expectations, or something odd with the puzzle, then they have to take another look. If identified as "something new," the scientist has another puzzle to solve or perhaps it is the same puzzle that must be put together in a different way. "I think that is how science evolves," said Dr. Hershall. Students experience similar situations, but often an anomaly is discarded or designated as "error." We should not deny our students the opportunity to learn about the subjective (theory-laden), creative, and tentative NOS associated with identifying and grappling with anomalous data

(Chinn & Brewer, 1993). Teachers might capture these opportunities to bring scientists' stories into the classroom that demonstrate similar NOS features from the view of scientists. Instructionally, examining and comparing stories and actual statements from history of science as well as contemporary scientists may be a useful approach to clarify overarching NOS aspects, and connections and interdependencies of those aspects, such as those targeted for K-12 science (Abd-El-Khalick & Lederman, 2000; Lederman, 2007; Osborne et al., 2003).

The words of Dr. Hershall and Dr. Ross can be used (1) to demonstrate the sophistication with which scientists can express their ideas and experiences of science when prompted to reflect; (2) as examples from two areas of contemporary science that highlight NOS features, and connections among those features, that are important for K-12 science instruction; (3) to demonstrate the integral role of model development and use in scientific investigations and progress, including identification of anomalies; and (4) to initiate discussion about how NOS is progressive and dynamic, as reflected in real examples that blur the boundaries between science and mathematics (e.g., string theory). Through these types of examples, I advocate that we provide learners multiple experiences and multiple contexts to learn about those aspects of NOS that *tie the disciplines together* as "science." These include aspects such as the inherent tentativeness of scientific knowledge, creativity, theory-driven and subjectivity, empirical basis, and that scientific knowledge is socially and culturally framed. These are characteristics that are advocated as appropriate for K-12 learners, and that are identifiable across scientific contexts, including the biochemistry and theoretical physics contexts of Dr. Hershall and Dr. Ross. The relationships and connections between these aspects are also highlighted through their stories. Others may promote context- or discipline-specific NOS instruction that emphasizes the uniqueness of different scientific practices (Rudolph, 2000, 2003; Samarapungavan, Westby, & Bodner, 2006; Wong & Hodson, 2009). I acknowledge the unique natures of these disciplines when examined from a fine philosophical lens; however, we cannot forget the goal of science education in preparing learners to be citizens and savvy consumers of science in the twenty-first century (Rutherford & Ahlgren, 1990). Helping learners see connections across contexts is essential for the transferability of their NOS understandings to new situations. As described by the scientists in this chapter, new situations are arising faster than ever within the scientific community.

Engaging learners in stories from real science (Ziman, 2000) and helping them compare these practices to classroom inquiries and reflect on NOS and inquiry aspects is an encouraging way to prepare tomorrow's citizens for tomorrow's science. Future research should explore the effectiveness of using scientists' case studies to advance learners' conceptions of NOS and the nature of scientific inquiry. Additional research is needed to uncover scientists' views of NOS and their stories that exemplify contemporary science practices, science progress, and the blurring boundaries at the cutting edge.

A Closing Reflection About Researching the Nature of Scientists' NOS Views

I learned from this work that a clinical approach to studying scientists' views yields very little useful information. Establishing genuine trust and interest is a key factor. How does a researcher do this? First of all, by being open and honest, available, and somewhat vulnerable. I was open and honest about my intentions of the study. I was available to whatever format they wanted to use for the data collection. I was vulnerable in that I was obviously not an expert in the science about which they talked, yet I was, again, honest about my intentions and genuinely interested in learning from these experts. We had conversations. The settings were not really important as long as the conversational style was established. Dr. Hershall and Dr. Ross welcomed me, offered respect, and hospitality. The advise I offer my fellow researchers is the same as I would offer fellow teachers: be patient and prepared and never judge. Keep the purpose in mind—What are their stories? What are their ideas? Why do they think the way they do?

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Chapter 9
The Nature of Science or the Nature of Teachers: Beginning Science Teachers' Understanding of NOS

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For over 100 years, understanding the Nature of Science (NOS) has been considered an important goal for all K-12 students and their teachers. Education researchers have long considered an understanding of NOS to be a critical component of education and science literacy (Lederman, 2007). Viewed as a "prized educational outcome" (Lederman, 2007, p. 831), NOS is generally referred to as "the epistemology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (Lederman, 2007, p. 833). Rather than describing the processes of science or the resulting knowledge that develops from engaging in processes of science, NOS represents the "epistemological underpinnings of the activities of science and the characteristics of the resulting knowledge" (Lederman, 2007, p. 835).

Secondary science teachers play a critical role in providing students with an understanding of NOS. It is important to explore beginning teachers' understanding of NOS because they are just learning to teach science (e.g., Adams & Krockover, 1997; Luft, 2001; Loughran, 1994; Simmons et al., 1999; Trumbull, 1999). As new teachers, they make instructional decisions by drawing from their emerging knowledge base. Most research on this subject has focused on preservice teachers, especially those participating in elementary science methods courses (Luft, 2009). The present study, conducted with semi-structured interviews over 3 years as part of a larger longitudinal study, focuses on beginning in-service secondary science teachers' understanding of NOS during their first years in the classroom. A rigorous examination of secondary science teachers' understanding of NOS may lead to greater insight into how NOS is developed and how a teacher understands the dynamic nature of the scientific process.

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Nature of Science and Science Education

In the early 1900s NOS was synonymous with the scientific method, but its conceptualization has advanced since then (Abd-El-Khalick & Lederman, 2000; Central Association for Science and Mathematics Teachers, 1907). In the 1960s, science educators focused on scientific inquiry and process skills, and in the 1970s they began to regard scientific knowledge as tentative, public, replicable, probabilistic, humanistic, historic, unique, holistic, and empirical (Abd-El-Khalick & Lederman, 2000). During the 1980s, observations were characterized as theory-laden, human creativity was recognized as an integral factor in scientific explanations, and the influence of science organizations, as well as the increased impact of social discourse, became part of the dialogue surrounding NOS (Abd-El-Khalick & Lederman, 2000). In the 1990s, the California Department of Education noted that "science depends on evidence and scientific activities are theory-driven and investigations are conducted from within certain frameworks of reference" (Abd-El-Khalick & Lederman, 2000, p. 668). The *National Science Education Standards[NSES]* (National Research Council [NRC], 1996) later added the roles of skepticism and open communication in science, along with the relationships between personal, cultural, and societal beliefs in advancement of scientific knowledge (Abd-El-Khalick & Lederman, 2000).

The importance of NOS has been discussed by several researchers, including Driver, Leach, Millar, and Scott (1996). This group identified five roles of NOS as critical to education:

1. To make sense of science and technology
2. For informed decision making
3. To value science in culture
4. To understand the moral norms of science
5. To facilitate learning science

As NOS has gained prominence in science education, Lederman (2007) has proposed the following six main facets of NOS that students should know:

1. Recognize the differences between observations and inferences, as observations are "descriptive statements about natural phenomena that are 'directly' assessable to the senses (or extensions there of) and about which several observers can reach a consensus with relative ease" (Lederman, 2007, p. 833) while inferences are statements that "go beyond the senses" (Lederman, 2007, p. 833).
2. Recognize the delineation between a scientific law and scientific theory, with the full understanding that theories do not turn into laws and that one is not valued more so than the other. Where laws are "statements or descriptions of the relationships among observable phenomena" (Lederman, 2007, p. 833), theories are explanations that are inferred from observable phenomena.

3. Recognize that scientific knowledge relies on observations of phenomena, as well as human creativity and imagination (Lederman, 2007). Along with rational and logical thought processes, creativity and imagination are required in order to conceive of explanations about the natural world.
4. Recognize that scientific knowledge is influenced by beliefs, prior knowledge, preparation, experience, and expectations. It is not only theory-laden, but also subjective to the individual (Lederman, 2007).
5. Recognize that science is embedded within sociocultural contexts in which it is heavily influenced by factors such as "social fabric, power structures, politics, socioeconomic factors, philosophy, and religion" (Lederman, 2007, p. 833).
6. Recognize that scientific knowledge is not absolute; scientific theories, laws, and facts are all subject to change as new evidence is discovered (Lederman, 2007).

Research into Teachers' Understanding of NOS

Research into teachers' conceptions of NOS has mainly focused on preservice elementary teachers. These studies have consistently reported that NOS should be explicitly taught in the classroom. For example, in order to improve a teacher's understanding of NOS, Gess-Newsome (2002) found that direct NOS instruction in an elementary science methods course resulted in participants holding a more sophisticated view of science as a body of knowledge. Similarly, Craven, Hand, and Prain (2002) found positive change in participants' language use to describe the nature and structure of the scientific enterprise after explicit instruction of NOS in a science methods course. While these and other studies show a positive relationship with explicit NOS instruction and participants' understanding of NOS, another group of studies suggests that teachers need specific instruction in order to use NOS in their classrooms. Bell, Lederman, and Abd-El-Khalick (2000) and Abell, Martini, and George (2001) found that preservice teachers who did not themselves receive explicit instruction about teaching NOS did not include NOS in their lesson plans. From this they concluded that direct instruction is required in order to increase a teacher's understanding and use of NOS.

Research pertaining to the actual use of NOS in the classroom among new science teachers is rare. While it seems that new science teachers who have explicit NOS instruction during their preservice program may use NOS in their classroom, there is little data exploring this assumption. Within this group of understudied teachers are those in the secondary classroom. As these teachers often represent the last opportunity for students to engage in NOS, it is important to know if secondary science teachers (who have content majors) do implement NOS in their classrooms. This is an important group of teachers to examine because they are most likely to implement NOS given their content background. Although Lederman (2007) suggests that academic background does not have an effect on a teacher's conception of NOS, clearly there is a need to explore the use of NOS among beginning secondary science teachers.

Assessing NOS

Measurement of NOS has been the subject of much debate. Many of the NOS assessment tools created since the 1960s have come under criticism. After reviewing various NOS instruments, Lederman, Wade, and Bell (1998) and Lederman, Abd-El-Khalick, Bell, and Schwartz (2002) found three main issues. First, data from the instruments can be interpreted in a biased manner. The problem with interpretation resides in the instrument construction, which often assumes only one way of thinking about NOS. However, those studying NOS have not reached consensus on the facets of NOS (Cotham & Smith, 1981; Lederman et al., 1998). In light of the fact that there is no uniform view of NOS, researchers must present their views, devise how to assess them, and collect and analyze data. This very process allows for bias because of the subjective nature of the methodology.

The second issue with some NOS assessments is that they appear to be constructed poorly (Lederman et al., 1998). Paper-and-pencil tests have been criticized for discrepancies between a participant's written responses and interviews. These tests have also been criticized for their limited assessment of understanding, as they often do not elicit how an understanding of NOS impacts behaviors and choices (Lederman et al., 1998). Interviews provide additional detail when compared to paper-and-pencil tests, but issues still persist with this method. For example, some interviewers do not record the questions they asked during the interview, which "prevents adequate assessment of the interview's validity and precludes the possibility of replication in other settings, not to mention the overall validity of the research findings" (Lederman et al., 1998, p. 610). Classroom documents and observations suffer from the same constraints as interviews because they often insufficiently describe the data collection and analysis process. Furthermore, they are often not explicit about how the results are integrated into the study's conclusions (Lederman et al., 1998).

The third issue concerns the usefulness of standardized instruments (Lederman et al., 2002). Standardized tests are appropriate for large-scale assessments, and for generating an adequate measure of various aspects of participants' understanding of NOS, but they typically categorize participants' views as "adequate or inadequate" (Lederman et al., 2002, p. 503). For example, *Wisconsin Inventory of Science Processes (WISP)* (Scientific Literacy Research Center, 1967) contained 93 statements that participants either categorized as "accurate," "inaccurate," or "not understood." "Inaccurate" and "not understood" were later combined when the assessment was scored. *Science Process Inventory (SPI)* (Welch, 1967) was a forced-choice instrument where participants could select "agree" or "disagree" on 135 items. Having only two categories that classified participants as to whether they held adequate or inadequate amount of NOS knowledge resulted in a narrow view of the participant's NOS knowledge. To further complicate the issue, in some cases in which numerical values were reported, the developers did not clarify the numerical values associated with an adequate or inadequate understanding of NOS (Lederman, 1986). It seems while, that standardized assessments were able to include a large number of participants, the findings did little to reveal a complete picture of the breadth or depth of the participants' understanding of NOS.

Of the instruments that were reviewed for Lederman's study, two assessed participants' views of NOS on a 3-point scale. The first study, *Views of Nature of Science (VNOS)*, assesses the participants' ability to express their views of NOS (Schwartz, Lederman, & Crawford, 2004). Preservice secondary science teachers' views of NOS were explored as they participated in a research internship course. Forms of data collection included interviews as well as the implementation of VNOS-C. After the analysis, the participants were rated with a "+" if they agreed that a specific aspect represented NOS, a "++" if the participant could express the meaning of the aspect in his/her own words, or a "+++" if the participant could express the meaning and provide additional examples (Schwartz et al., 2004). Although VNOS-C used a 3-point scale, the focus was on the participants' ability to express their views of NOS. In other words, this analysis using the VNOS-C questions appears to assess participants' ability to communicate their views of NOS instead of their actual understanding of NOS.

The second research project that employed an instrument with a 3-point scale was undertaken by Lotter, Singer, and Godley (2009). In their study, they followed nine secondary science teachers through three cycles over approximately 7 months. Each cycle consisted of practice teaching and reflection that emphasized foundational pedagogical ideas for middle- and high-school classroom settings. Utilizing multiple sources of data, including interviews implementing Lederman's (2005) *Views of Scientific Inquiry (VOSI)* instrument, reflection papers, and teacher portfolios, they found that teachers improved their utilization of NOS and inquiry in the classroom. Using a 3-point scale allowed Lotter et al. (2009) to document the growth of preservice teachers as they varied between "naïve," "transitional," and "informed." Participants with the lowest level of NOS understanding were labeled "naïve" when they held numerous misconceptions about NOS. Respondents were labeled "transitional" if they held views that partially matched reform statements, but contained some misconceptions. If the participant was placed in the "informed" category, he or she viewed NOS as an orientation that included multiple methods and collaborative endeavors, and acknowledged the impact of social, cultural, and personal aspects on an individual's ideas (Lotter et al., 2009). This type of scale is feasible for large-scale studies, which are beneficial in generalizing conclusions to a larger population.

Study's Rationale

A review of the literature has pointed out a clear trend in preservice elementary teachers' understanding of NOS. As shown by the existing research (i.e. Abell et al., 2001; Akerson, Abd-El-Khalick, & Lederman, 2000; Craven et al., 2002; Gess-Newsome, 2002), most studies focus on preservice elementary teachers participating in a science methods course, with conclusions that reveal the need for explicit NOS instruction. Currently, there is limited work on beginning teachers, specifically secondary science teachers who are in their first 3 years in the classroom. Content specialists, such as beginning secondary science teachers, have unique pedagogical and content considerations (Stodolsky & Grossman, 1995). By looking at the NOS (and other forms of knowledge) of beginning secondary science teachers it is possible to gain insight into how teachers build their knowledge during this formative time (Luft, 2007).

Our review of the research also led to the conclusion that most tools used to assess NOS are based on a 2-point scale that categorizes participants as either those that understand NOS, or those that do not. Similar to Lotter et al. (2009), the present study implemented a 3-point scale to provide a more nuanced examination of secondary science teachers' understanding of NOS. Four factors set this study apart from the previous research that has been done in this area: (1) The participants were practicing beginning secondary science teachers in five different states throughout the United States. (2) This study was relatively large scale, with 73 participants in comparison to such studies as Lotter et al. (2009). (3) This study also addresses one of Lederman's (2007) fundamental questions: "How do teachers' conceptions of NOS develop over time?" (p. 869). This study explored secondary science teachers' NOS understanding over a 3-year period in which data collection began before the teachers started teaching and ended with the last data collection point after their third year in the classroom. (4) Unlike other NOS studies, including that of Lotter et al. (2009), this work focused on practicing teachers that were not participating in interventions designed to explicitly address aspects of NOS. Whereas other studies evaluated the impact of an intervention on preservice or in-service teachers' conception of NOS, this study explored changes in NOS understanding without providing professional development designed to address aspects of NOS.

This study fills a void in the literature in that it is a large-scale longitudinal study focused on beginning secondary science teachers' NOS understanding, with semi-structured interviews as the method of data collection.

Research Questions

In this study we address issues concerning the gap in the literature on the development of NOS understanding in induction teachers. Specifically, we focus on studying a large group of beginning secondary science teachers longitudinally, while emphasizing the effectiveness of a more fine-grained scale in the analysis of NOS. This study is guided by the following questions:

1. Does the new procedure of analysis create a more complete understanding of the individual teacher's understanding of NOS?
2. Are there any significant differences between different induction groups of teachers in their understanding of the nature of science?

3. Do differences in the demographics of teachers, such as the highest degree attained prior to entering the classroom, the subject in which this degree was attained, the number of History and Philosophy of Science classes, or the gender of the teacher correlate with significant differences in teachers' understanding of NOS over time?

Research Setting

This study resided within two research projects that followed beginning secondary science teachers over a 5-year period: Exploring the Development of Beginning Secondary Science Teachers and Persistent, Enthusiastic, Relentless: Study of Induction Science Teachers (PERSIST). Funded by the National Science Foundation, the studies were designed to explore the impact of four different types of induction programs on beginning secondary science teachers located in five states of the Southwest and Midwest regions of the United States. The induction groups involved were categorized as "General," "Intern," "science-specific (ASIST)," and "electronic mentoring (eMSS)." General group teachers received support from their school or district and focused on topics like teaching strategies and administrative responsibilities. Intern teachers received support from their schools but did not have a formal teaching certificate and were in pursuit of certification while teaching. Teachers in the science-specific induction program received monthly face-to-face mentoring by science teacher educators or science teachers at a university in the Southwest. This program was referred to as Alternative Support for Induction Science Teachers (ASIST). Teachers in the electronic mentoring program also

Table 9.1 Induction programs studied

General	Intern	ASIST	eMSS
• School or district program • Assigned mentor is a teacher that may or may not be in field • Focus on general induction • Meetings vary	• Educational coursework while learning to teach • Mentors may or may not be in science • Focus on general instruction	• University developed • Focus on teaching science • Faculty and district mentors • Monthly classroom visits, monthly university sessions, annual science education conference	• University and organization developed • Focus on science teaching • Mentors who are experienced teachers • Active on-line community • Meeting once a year

received science-specific support but did so by participating in an online community and meeting face-to-face once a year. This program was referred to as electronic Mentoring for Student Success (eMSS). The induction programs (General, Intern, ASIST, and eMSS) lasted for the first 2 years for all teachers, although the intensity of the second year varied among programs. An overview of the induction programs studied in both projects can be found in Table 9.1 (adapted from Luft, 2009), while a complete discussion of the research project can be found in Luft (2009).

Methods

Participants

This study uses the data from 73 teachers located in five states in the United States (Table 9.2). Overall, the teachers included were mostly female, held bachelor's degrees, and resided in the Southwest or Midwest regions of the United States. The teachers in this pool participated in one of four identified induction programs which have been described previously: General (GEN), Interns (INTERN), science-specific (ASIST), or electronic mentoring (eMSS). For this study, however, the data is drawn from teachers who participated during the first 3 years of the study. Those that did not complete interviews during all 3 years of data collection were excluded since these points of data were critical in studying teacher change over time.

Data Collection and Analysis

The data collected in this study consisted of interviews, which included both questions pertaining to demographic information and the teacher's knowledge of NOS. The demographic questions included the type of induction program in which the teacher was enrolled, the highest degree that the teacher had completed prior to teaching, the subject in which the teacher had a degree, whether the teacher took

Table 9.2 Participant demographics

	Gen	eMSS	ASIST	Intern
Total	21	23	20	9
Male	10	6	8	1
Female	11	17	12	8
Type of school				
Middle school	6	6	6	3
High school	15	17	14	6
Academic preparation				
BS/BA	16	17	16	7
MA/MS	5	6	4	1
PhD/EdD	0	0	0	1

courses in the History and Philosophy of Science and how many courses he or she may have taken, and the gender of the teacher. These items were used to explore potential relationships between NOS and different demographic areas.

The teachers' understanding about NOS was captured through the interview protocol "Views on the Nature of Science-C" (Abd-El-Khalick, Bell, & Lederman, 1998). An additional question was added that focused on how teachers represented the discipline of science in their classrooms (Brown, Luft, Roehrig, & Fletcher, 2006). Semi-structured interviewing was the process utilized for data collection due to its adaptability during an interview (Fylan, 2005). The flexibility of semi-structured interviews allowed the researcher to modify or expand a question in order to gain greater understanding of the topic (Fylan, 2005). Semi-structured interviews also allowed for access to a teacher's thinking process that could not be obtained through observation or other data collection methods.

Teachers were asked all of the interview questions by a research assistant trained in the protocol and trained to follow up on specific responses related to the NOS questions. The research assistant who conducted the interview also digitally recorded the interview for later analysis. Extensive notes pertaining to the interview were also taken for later analysis.

Two other research assistants were responsible for coding the teacher's responses. They did this independently using the rubrics developed for the project (see Brown et al., 2006). After the responses were coded individually, both research assistants met and discussed their codes. Through a process of consensus, the two independent researchers collaborated to reach unanimous agreement and resolution (Herrera, Herrera-Viedma, & Verdegay, 1996). The final coding was rated as "product," "process," or "situated" based upon what the teachers stated were important in terms of their understanding of NOS.

Responses that were rated as "product" were quantified as a score of 1 and reflected a view of science solely based upon facts and data. These teachers tended to view science as more "static," with changes in science resulting from improvements in technology. In addition, they tended to believe that there was "only one way to 'do' science." For example, a product response from a participant regarding scientific method would be, "Scientists follow a universal method which involves objective observation, experimentation, and comparison."

Responses that were rated as "process" were quantified as a score of 2 and represented a transitional stage between the two extremes. The teachers' views of science could be considered both "static" and "dynamic" in terms of the development of science over time, the roles of the scientific method and experimentation, and how science was represented in their classrooms in contrast to being conducted in "real-life." For example, a process response to questions regarding scientific method would be, "Scientists do not follow a definitive method, but rather a general method, where hypotheses are proposed and tested through experiments, and the process is repeated in a cycle, with the strongest theories surviving."

Responses that were rated as "situated" were quantified as a score of 3, and were associated with a more philosophical outlook of science that included relevance of the students' experiences and the subjective nature of scientific analysis

(Feyerabend, 1975). These teachers described multiple methods for conducting and representing science in their classrooms. For example, a situated response to questions regarding scientific method would be similar to, "There is no one scientific method. Different scientists use different methods to arrive at their findings, and methods are determined by the parameters of the field or paradigm. The focus was on the role of evidence and explanation rather than the methodology."

After each interview was quantified, a mean NOS score for each teacher was derived from their responses to the VNOS-C prompts. This process follows Lederman's (2000) recommendation in determining the understanding of NOS among participants. Lederman (2000) points out that there is no singular question that depicts NOS, or a particular answer that reflects understanding of NOS. In fact, quite often teachers will hold mixed or contrary views about NOS depending on the subject. For example, a teacher might be considered "situated" in terms of his or her understanding of the scientific method, but responds in a "product" fashion in terms of his or her understanding of the roles of theories and laws in science. Therefore, separating the VNOS-C into individual questions for analysis does not yield a complete characterization of a participant's understanding of NOS.

These mean scores were averaged and the standard deviations calculated by group (e.g., Gen, Intern, ASIST, eMSS) and by groups over time. In addition, analyses of induction groups and various demographic characteristics were conducted to determine if there had been a change in the understanding of NOS during the first 3 years in the classroom. These analyses were done using an Analysis of Variance (ANOVA) and a series of two-way repeated-measures ANOVAs.

Coding Example

The following is an excerpt from an annual interview with Molly (pseudonym). It is followed by the explanation of how the final score was reached via the consensus model:

Interviewer: What are the roles of theories and laws in science?

Molly: Let's start with laws. Laws are easier to understand. Laws are more things you could think in terms of repeatability. Or predictive things that become laws… Maybe even calculate out what would happen because of a law.

Interviewer: Can you give me an example?

Molly: Like Newton's laws of motion. You can use his equations to figure out at what rate something is going to accelerate due to gravity. You can calculate that, predict it, and it's repeatable.

Interviewer: Ok. What's a theory?

Molly: A theory is based on scientific facts. And it's repeatable. Like the theory of evolution. You have the theory of evolution where you can go and you can show all kinds of data backing up that theory of evolution, yet you don't have concrete equations that this predicts that you can calculate out the next step.

Interviewer: How would you make a distinction between a theory and a law?

Molly: I would say that a law would give you concrete equations that you can apply all the time and that they would give you predictive capabilities. And a theory gives you evidence and give you trends, but it won't give you concrete predictions. Like the theory of climate change. We have evidence. We have a lot of concrete evidence. We have observations we can use in there. We can use that evidence to create models to start to predict things but don't have enough concrete predictive powers in there.

Coder 1 rated the response as "process/2" because Molly's response focused on laws being repeatable with the ability to predict certain expected outcomes, while theories are also repeatable but are not as appropriate for predicting outcomes. The focus on repeatability supports the notion that laws and theories have survived attempts at falsification through experimentation because both are repeatable, but Molly separated them due to their ability to predict. Although it appears that Molly was not clear on the distinction between theories and laws, coder 1 did not rate her as "product/1," because Molly's response did not indicate that theories and laws explain regularities without exception, nor a "situated/3," because she clearly did not view both theories and laws with predictive powers.

Coder 2 rated the response as "situated/3," because Molly indicated that theories and laws had distinct roles and that one could not become the other over time. In addition, Molly emphasized the idea that theories and laws were used to model science and not as the "goal" of science. Finally, Molly indicated that the role of theories and laws was to predict "things." After both coders separately arrived at their codes, the codes were compared to each other and discussed in order to arrive at a consensus. During the discussion of the coding of Molly's responses it was decided that her answers were more indicative of a "process" categorization and were not developed enough to be categorized as "situated."

Comments About the Methods

This study is different from other studies that look at the NOS of beginning science teachers. First, our sample size is significantly larger than most. The majority of studies of this type usually are comprised of small numbers of participants—typically no more than 10 or 12—enrolled in either a particular class or classes as part of their preservice program, or a small group of teachers involved in professional development activities. As a part of a larger longitudinal study, we followed a large population of teachers ($N = 73$) for a period of 3 years.

All of the teachers in this study were interviewed, once per year. The length of time of the study and the long period between the interviews provided a much larger scope of data from which to draw. Previous studies measuring change typically looked at data over a period of days or weeks. A short data-collection cycle limits the factors that influence change in the understanding of NOS, but it does not provide an opportunity to look at possible factors that contribute to a change in the teachers' understanding of NOS over time.

There are also some limitations pertaining to this process that need to be discussed. The first of these concerns is validation. Due to the nature of the study there was no attempt to triangulate the results with other data vectors. For instance, the researchers did not collect additional NOS related data throughout the course of the study. In order to address this issue, the researchers recommend additional data sources be used as part of the overall assessment of the understanding of NOS. These could include portfolios, observations, analysis of lesson plans in terms of NOS, or questionnaires completed by the teachers.

A second consideration is the calibration of the instrument. The three-point scale used to assess understanding may need adjustment in order to make the relative differences between the three categories more uniform. At this point, the "product" and "situated" categories represent endpoints on a linear scale. However, the "process" category is not specifically tied down to the center of this scale. That is, the process responses to the interview may expand the middle range of the scale. This is a problem to consider, and with further development of this scale there will have to be an examination of the range of the different codes.

Results

There are four different questions guiding this study. The quantitative analysis results are shared first, and then there is a discussion of the 3-point analysis process in the discussion part of this chapter.

The first quantitative question asked if "there was any significant difference between different induction groups of teachers in their understanding of the nature of science?" Simply put, there were no significant differences in understanding among the teachers in the different induction programs ($F(3, 70) = 1.27, p = 0.29\,1$).

The second quantitative question asked if "differences in the demographics of teachers, such as the highest degree attained prior to entering the classroom, the subject in which this degree was attained, the number of History and Philosophy of Science classes, or the gender of the teacher, correlated with significant differences in teachers' understanding of NOS over time?" In terms of the effect of induction program over time, there was no significant difference ($F(9, 210) = 1.29, p = 0.24$).

The highest degree completed by the teacher (bachelor's, science MS, Education MS or MEd, PhD/EdD) over time was significant. Different levels of education produced significantly different NOS scores. In addition, the interaction of highest degree completed and time was also significant. Different education levels produced significantly different changes in the understanding of NOS over time. Main effect differences were found between teachers with a BS and an MS ($M_D = 0.669$, $SE = 0.162$, $p < 0.001$) (see Fig. 9.1).

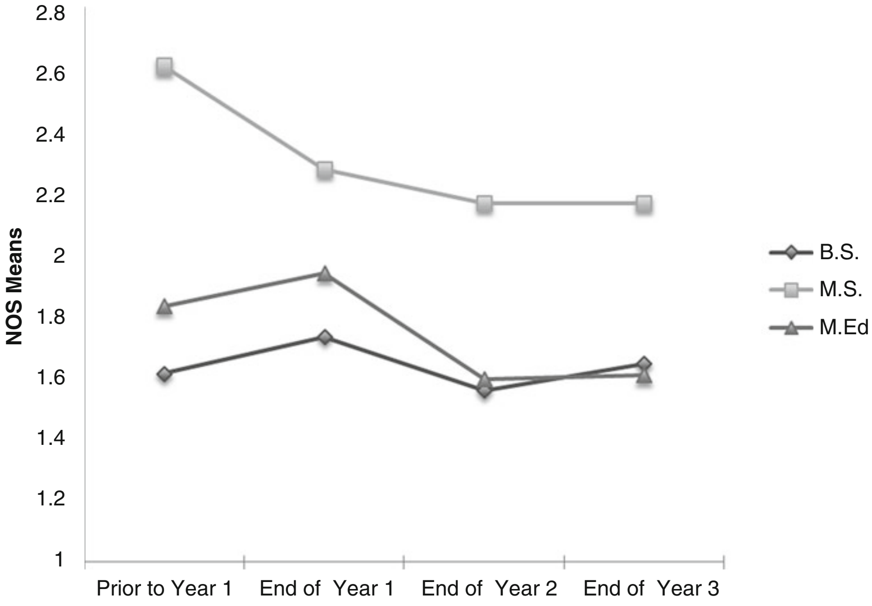

Fig. 9.1 Highest degree completed

The content area of the teacher's degree (life science, chemistry, physics, earth science, other science, engineering, non-science) over time was significant. Different majors produced significantly different NOS scores. In addition, the interactions of content area with time were also significant. For example, teachers with majors such as physics produced significantly different changes over time in comparison to teachers with non-science degrees. Main effect differences were found between teachers who had a degree in Physics and those who had non-science degrees ($MD = 0.688$, $SE = 0.196$, $p = 0.001$) (see Fig. 9.2).

The effect of the number of History and Philosophy of Science (HPS) classes over time were also significant. In addition, the interaction of the number of HPS classes with time was also significant. Specifically, there was a significant difference between teachers who had not taken a HPS class and those who had taken more than one. Main effect differences were found between teachers who had not taken an HPS course and those who had taken more than one HPS course ($MD = 0.354$, $SE = 0.077$, $p < 0.001$) (see Fig. 9.3).

The gender of the teachers was also significant. Male teachers scored significantly higher than female teachers throughout the study. The interactions of gender and time were also significant. As for the main effect of gender, main effect differences were found between male and female teachers ($MD = 0.214$, $SE = 0.069$, $p < 0.005$) (see Fig. 9.4).

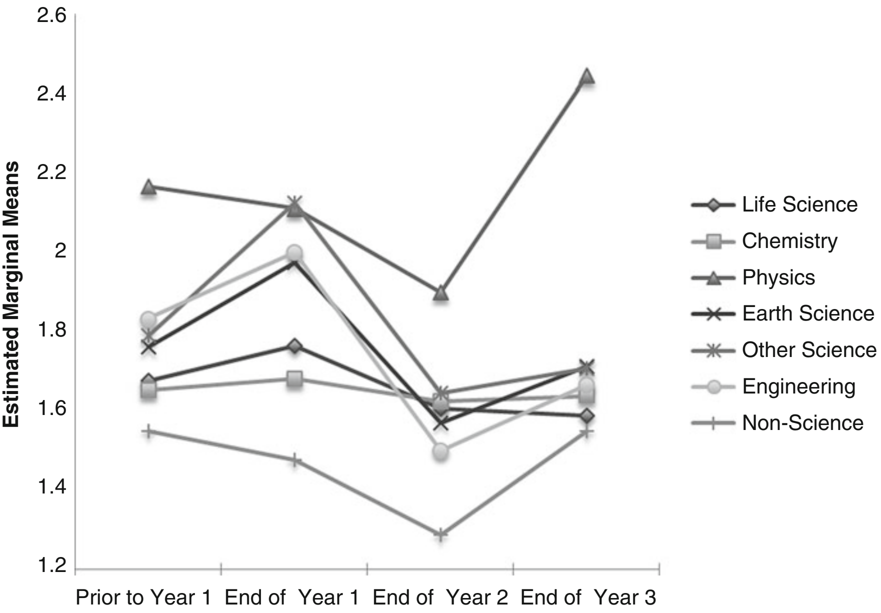

Fig. 9.2 Degree subject

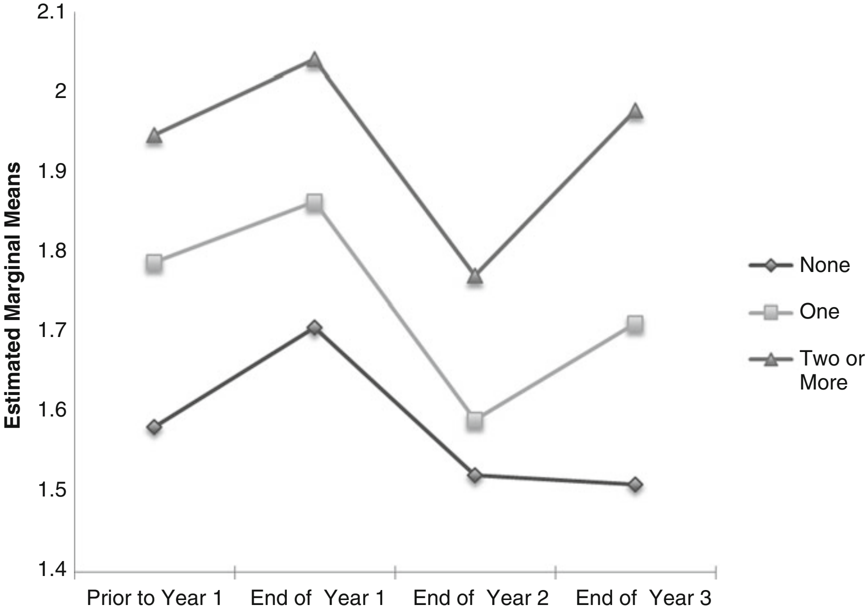

Fig. 9.3 Number of history and philosophy of science courses

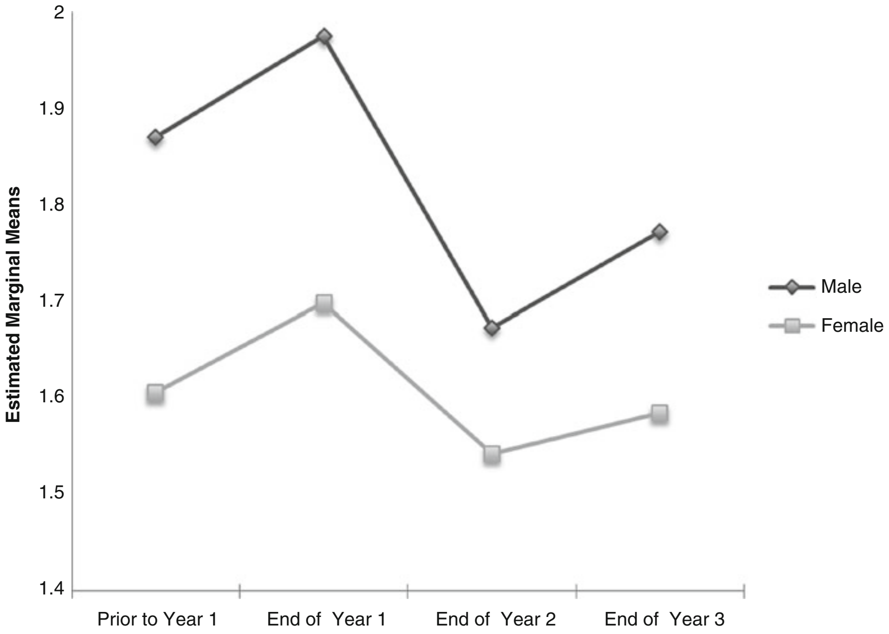

Fig. 9.4 Gender of teacher

Discussion and Conclusions

There are two important points to discuss from the analysis of data. First, the results of this study agree with other recent studies (Lotter et al., 2009), indicating that the educational background and experiences of beginning secondary science teachers have an impact on their understanding of NOS. Previously, it was believed that only direct instruction as part of some form of intervention had any effect on a teachers' understanding of NOS. Therefore, the results of this and other recently published studies run contrary to previous notions of how science teachers' understanding of NOS develops. Furthermore, the data give insights into how beginning science teachers change during their first 3 years in the classroom. The large sample size and length of the study allowed the researchers to examine how aspects of previous education, preservice program, and content taught as new teachers, impact understanding of NOS over time. These results indicate that a teacher's understanding of NOS is fluid; it interacts with the background and ongoing teaching experiences of the teacher as he or she develops. However, because beginning science teachers' understanding of NOS may be more tentative than that of experienced science teachers, they may be more likely to change their understanding of NOS. Continued study of these teachers into their fourth of fifth years may reveal a stabilization of their understanding of NOS.

The second point pertains to the first question in this study: "Does the different coding system provide a better understanding of the NOS knowledge a teacher holds?" From this study, it seems that it does. By including a "process" or "transitional" category for the assessment of the understanding of NOS, responses that would have previously been coded as "developed" or more likely "naïve" could be assigned to a more accurate middle ground category. This middle category, therefore, allows for a more "fine-grained" assessment of the teacher's understanding and perhaps unmasks change that had previously been hidden within a binary scoring system. This use of a middle category can be seen in the paper of Lotter et al. (2009). Without a third "transitional" category, many of her participants may have been labeled with no change after her intervention.

Summary

This study differs from previous work in four important ways. First, we followed beginning secondary science teachers through their first 3 years instead of studying groups of teachers in a smaller time frame. This length of time allows for capturing a change in NOS over time. Second, our study also differs from other studies because it followed a large sample as compared to smaller samples of teachers. With a larger number of teachers in the study, there is more potential for generalization. Third, our participants did not undergo explicit NOS interventions, unlike studies that examined the impact of purposefully designed NOS instruction. In this longitudinal study we have found, contrary to past and current literature, that experiences of teachers prior to and during preservice may have a profound impact upon their understanding of NOS. Our study pinpoints several factors that impacted our participants' understanding of NOS and how their understanding had changed during the induction years.

From this study, it seems clear that in order to capture more precisely a teacher's understanding of NOS prior to, during, and after interventions, new NOS instruments should be created or existing instruments should be recalibrated. Future work that builds upon the findings of this study would allow researchers and science educators to design and implement NOS interventions that support the development of the knowledge base. Additional studies should examine teachers' understanding of NOS from before preservice education through their first 5 years in the classroom. In particular, further studies should delve into the reasons why particular factors found in this study—such as degree, context area specialization, number of history and philosophy of science classes, gender—affect teachers' understanding of NOS. In sum, additional studies are needed in order to gain a more comprehensive understanding of NOS knowledge development in secondary science teachers.

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Chapter 10
Learning About Nature of Science in Undergraduate Biology Laboratories

Elisabeth E. Schussler and Nazan U. Bautista

Introduction

This chapter reflects on our experiences implementing a project designed to promote nature of science (NOS) understanding in undergraduate students taking an introductory biology laboratory at a mid-sized American university. We first provide the rationale for our study by summarizing the current state of large introductory undergraduate science laboratories in the United States and providing a literature review on NOS understanding of undergraduate students. Next, we briefly describe our research design, implementation, and assessment of the effectiveness of our project. The chapter ends with a reflection on the project implementation and modifications we would suggest for others wishing to promote NOS understanding in undergraduate science students.

Undergraduate Introductory Science Curriculum

Undergraduate students pursuing a science degree in the United States engage in a sequence of coursework that almost always starts with an introductory biology survey course. This course typically includes a lecture and laboratory component and lays the foundations of biological understanding for all further coursework. Although challenged in recent curriculum reform debates (Alberts, 2009; Committee on Prospering in the Global Economy of the 21st Century, 2007), most of these courses have traditional learning goals focused on content and sometimes process skills with little discussion of NOS understanding.

At institutions where classes last one semester, these courses typically meet 3 h/week for lecture, which is usually taught by a faculty member. Laboratories generally meet once a week for 2 to 3 h, and are taught by graduate teaching assistants

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(GTAs) at 71% of the comprehensive universities and 91% of the research universities (Sundberg, Armstrong, & Wischusen, 2005) in the United States. The level of integration between lecture and laboratory varies widely, particularly at larger institutions where the introductory courses are delivered in multiple lecture sections and the laboratories may be coordinated by faculty who do not teach the course.

Laboratories have been a traditional part of science curricula for well over 100 years, yet the learning goals for these experiences are often ill-defined (Hofstein & Lunetta, 2004). Some say that hands-on activities that elucidate scientific content are the major purpose of laboratories. Others see laboratories as a place to practice technical skills, while others think they should assist students in learning how to perform scientific investigations. The trend in recent years has been to move toward inquiry-based laboratory activities and away from what has been termed "cookbook" style laboratories in which students follow a defined procedure to reach a predetermined conclusion. Seventy-five percent of universities now include some form of inquiry laboratory experiences for their students (Sundberg et al., 2005). Arising from constructivist learning theory (Driver & Oldham, 1985), inquiry-based laboratories have students take more control over many stages of the investigative process, including generating hypotheses and designing experiments, and focus more heavily on interpreting and justifying conclusions for open-ended investigations.

As mentioned previously, the instruction for most undergraduate science laboratory classes is directed by graduate teaching assistants (GTAs) and not faculty members. GTAs who teach undergraduate laboratories typically do so to fulfill the obligations of their university assistantship, which is their main financial support for graduate study. They are usually expected to spend up to 20 h/week on this appointment, including, but not limited to teaching a certain number of laboratory classes (usually two to three), attending laboratory preparation sessions, grading laboratory work, meeting with students, and sometimes attending the lecture class and/or proctoring for lecture class exams. Because GTAs were "hired" primarily to conduct research at the university, some graduate advisors implicitly or explicitly advise their graduate students to spend as little time as possible on their teaching duties (Kurdziel & Libarkin, 2003). Given the diversity of ages, teaching experience, motivation to teach, lack of support and training, and pressure to do research, GTAs assigned to teach introductory science laboratories have inherently different levels of instructional ability.

Professional development for GTAs has long been a concern in academia, but institutional implementation of meaningful training has been limited (Luft, Kurdziel, Roehrig, & Turner, 2004; McComas & Cox-Petersen, 1999). The most common form of training are university-wide new GTA orientation sessions, typically lasting no more than a day and mainly covering institutional policies. Some departments have their own GTA orientation sessions, but very few focus solely on developing disciplinary teaching skills. Some universities have instituted semester or year-long GTA professional development sessions or offer courses on teaching in higher education or science education. For the most part, however, these types of courses are voluntary.

The reality of undergraduate science laboratories is that the course objectives are not always clear and GTAs do not receive an adequate amount of instructional support for the duties they perform. These courses, particularly at larger institutions, also may experience a lack of coordination between faculty who teach the lecture course, faculty who direct the laboratories, and GTAs who teach the laboratories. These factors probably contribute to the dearth of large-scale curriculum reform projects in undergraduate science laboratory courses.

NOS and Undergraduate Students

It has only been in the last decade or so that science departments have begun to consider the explicit inclusion of NOS as a learning objective for their science courses. For many years, NOS was viewed as a learning outcome that students would "pick up" along the way as they engaged in science learning (Lederman, 1998). Particularly in the sciences, where students were engaged in laboratory investigations, there appeared to be no need to specifically discuss NOS.

Investigations into how well undergraduates understand NOS and how this understanding develops have led to the conclusion that students enter college with many misconceptions and incomplete understanding regarding NOS (Abd-El-Khalick, 2006; Fleming, 1988). They often have difficulty accurately distinguishing theories and laws (Abd-El-Khalick, 2006), fail to understand the complexity and explanatory power of theories (Dagher, Brickhouse, Shipman, & Letts, 2004), rigidly adhere to the scientific method as the way science occurs (Gilbert, 1991), and deny the subjective NOS (Bezzi, 1999; Ryder, & Leach, 1999). Indeed, science graduate students and science faculty have been found to have an incomplete understanding of NOS (Schwartz & Lederman, 2008).

In general, the agreed upon approach to teaching about NOS is called "explicit and reflective." The term "explicit and reflective" (ER) means that the learning objectives for NOS are made explicit to students, who are provided with structured opportunities to reflect on their understanding of NOS within the context of course activities. ER treats NOS understanding as an important outcome that must be planned for, taught, and assessed just as other course outcomes are. This technique arose out of pre-service teacher education (Akerson, Abd-El-Khalick, & Lederman, 2000) and has been used in pre-baccalaureate education (Akerson & Volrich, 2006; Khishfe, 2008; Khishfe & Abd-El-Khalick, 2002). Also, there have been successful applications of this technique in higher education in science methods courses for pre-service teachers (Abd-El-Khalick & Akerson, 2004; Gess-Newsome, 2002) and in a college physics course for pre-service science education majors (Hanuscin, Akerson, & Phillipson-Mower, 2006). However, the lack of studies in undergraduate science courses makes it hard to generalize whether ER works for all populations of college students.

The integration of NOS into science laboratory classes has been much less studied, particularly in colleges and universities. In general much of this may be because of the already low level of discussion and reflection that occurs in laboratories

(National Science Foundation, 1998). The general paradigm in laboratory classes is to enter the lab, listen to a short lecture on the day's topic, and then collect data until laboratory is over. Students sometimes compile and present data in class, but organizing, evaluating, and interpreting data are typically done outside of class time, and defending and discussing data or the process of science are practically nonexistent (Osborne, 2010).

The way that science is presented in introductory science classes and their associated laboratories also works against effective NOS instruction. Although these misconceptions have begun to disappear, some introductory science textbooks still present information on the scientific method as though it is the only way science progresses and emphasize the controlled, experimental nature of science (e.g., Sadava, Heller, Orians, Purves, & Hillis, 2008). Theories and laws are sometimes presented as a stepwise progression from hypothesis to theory to law. Books, faculty, and GTAs often refer to the strict objectivity of scientists, and the only acknowledgment of creativity is during experimental design, if that is even a part of the laboratory. Laboratories that focus on cookbook procedures serve to reemphasize these misconceptions by presenting science as purely experimental, with no room for creativity, focusing on objective measures of right and wrong to reach a clear answer. It is hard to imagine that students could gain an appropriate understanding of NOS under these conditions.

Project Rationale

As curriculum reform efforts have shifted laboratories away from cookbook approaches and toward inquiry-based activities, there are new opportunities to foster discussions about NOS and the process of science. If students are generating their own hypothesis, they could also discuss the theories that helped them frame their ideas. Students should also recognize that the process of science is not linear, and that it takes an enormous amount of creativity to infer explanations from observations. This understanding in turn helps students become better scientists by fostering their ability to make and defend meanings from their laboratory experiences (Berland & Reiser, 2009). These opportunities, however, can only be provided to students in an explicit and reflective setting.

Given the realities of the undergraduate science laboratory, we knew it would be challenging to redesign the curriculum to promote NOS understanding; however, we were also in an ideal position to foster reform. The university was supporting curriculum reform efforts to increase student classroom engagement, and we received a grant from the National Science Foundation to reform the laboratories. This combination of resources and support gave us the leverage we needed to undertake the project.

We also had multiple laboratory sections to implement the reform in an experimental design. Therefore, our study explored the effectiveness of an ER approach, in combination with inquiry or expository laboratories, in increasing undergraduate students' and GTAs' understanding of NOS. In fall 2008, two laboratory treatments

(ER vs. no ER or inquiry vs. expository) were delivered via a factorial design of four treatment combinations in 31 laboratory sections: 8 expository (E; $N = 143$ students), 7 E + ER ($N = 123$), 7 inquiry (I; $N = 142$), and 9 I + ER ($N = 194$); 17 GTAs were involved in the instruction of these 602 undergraduate students.

Implementation of the Curriculum Project

Context

The project team was critical to the implementation and consisted of five faculty members with different perspectives on the course. The project leaders were a science faculty member (Schussler) and a teacher education faculty member (Bautista) whose research interests were in science education, and who were both interested in NOS. The science faculty member also had taught one of the course lecture sections for the past 3 years. Of the other three team members, two were science faculty who taught the lecture portion of the course, one of whom was a former course coordinator, one the current course coordinator, and the final project team member was the laboratory coordinator. In addition to these faculty members, two graduate students worked as research assistants; both had taught introductory science laboratories prior to the appointment.

The Introductory Biology course affiliated with the project was a two-semester sequence, which at this particular university was for mixed majors, although almost all students who took it intended to major in the Biological Sciences or other science disciplines. The first semester of the course covered ecology, evolution, genetics, and biodiversity, while the second semester covered cell biology, metabolism, DNA, reproduction, and physiology. The courses were each four credit hours, with a 2-h laboratory each week. There were three lecture sections, each was team-taught by three faculty from Biological Science departments. Each lecture section served approximately 200–250 students, and was split into about 11 laboratory sections with up to 24 students each.

The laboratories were taught by GTAs from the Biological Science departments or Environmental Science program. Each GTA taught two laboratories, attended a weekly laboratory preparation meeting, and was responsible for laboratory grading. Many of the GTAs who taught the laboratory were first-semester graduate students. GTAs at this university attend a short university-sponsored orientation covering university policies, and then attend a 1–3-day orientation for their department, in which good teaching practices are presented in addition to other departmental issues.

Design of the Inquiry and Expository Curricula

The laboratory associated with the first-semester course, which was the focus of this project, had not been revised in a number of years, and featured mainly cookbook laboratories in which students verified known results. In some cases the laboratories were demonstration exercises, where students observed slides or preserved specimens. The main goal of the old version of the laboratory was to support the content learning in the course.

The revision officially began in January 2008 when the two graduate research assistants and project team began to rewrite the laboratories. The plan was to first create the inquiry and expository versions of the laboratories that would be used in the project, and then create the associated ER materials that would match with the content and procedures addressed in those laboratories. Our initial thought was to use the existing laboratories as the expository treatment laboratories, and create inquiry laboratories from them. We quickly discovered, however, that many of the laboratories lacked a scientific question that would lend itself to conversion to inquiry, and that the single-week length of most laboratories was not conducive to inquiry methods. By February the team had decided that the best course of action would be to create inquiry laboratories first, and then convert them back into expository laboratories. The project team brainstormed ideas for seven laboratories, some of which were 2- to 3-week laboratories, in which students would use different organisms to explore conceptual topics related to the course.

As the project team and graduate assistants struggled with creating and defining the laboratory exercises with the limitations of materials, time, and student numbers in mind, it became clear that we were also struggling with how to delineate inquiry from expository. Although we anticipated having difficulties defining inquiry—and we did have philosophical arguments over this – our biggest surprise was our struggle to define what constituted an expository experience.

In April, we met with the project's external and internal advisory board, who recommended the use of the Schwab/Herron levels of inquiry (Table 10.1, as cited in Colburn, 1997) for us to delineate our expository and inquiry laboratories. Accordingly, we revised our laboratory drafts so that our expository laboratories corresponded to a level 0 and our inquiry laboratories corresponded to a level 2. The advisory board was also critical in providing feedback and evaluation of the laboratories to affirm that they met the treatment criteria acceptable for the research design.

By early summer, the team had produced six treatment laboratories which underwent pilot testing. Each inquiry and expository version of the laboratory was performed in its entirety by small groups of undergraduate students led by a GTA in June and July 2008. Each piloting session took about 2 h and mimicked the

Table 10.1 Schwab/Herron levels of openness

Level	Problem	Ways and means	Answers
0	Given	Given	Given
1	Given	Given	Open
2	Given	Open	Open
3	Open	Open	Open

way an actual lab would be run. A project team member observed the session, and then led a feedback session with the students afterward. The feedback session consisted of written as well as verbal feedback about the procedures and what students had learned. Feedback was also collected from the GTAs who had led the session. Based on this process, one laboratory was removed from the project because it was logistically difficult, material and space-intensive, and most importantly, it failed to achieve the content learning objectives. The rest of the laboratories underwent a final revision.

At the end of the summer, we had five treatment laboratories (inquiry and expository) which lasted 10 weeks of the semester. The biology content, techniques, organisms, equipment, basic activities, and time on task were similar for all laboratories; the only variation was the pedagogy used to teach the laboratory.

Design of the ER Curricula

Once the laboratories were finalized, the ER approach was prepared for the expository and inquiry versions of each laboratory. Given that the content and procedures were similar for each laboratory, the modules that were created were the same for each version of the laboratory. We selected and focused on five aspects of NOS for the project: tentative, observation/inference, creativity, theory-laden, and myth of the scientific method. We chose these aspects because they were the most suitable given the science content of the laboratories and because they seemed the most accessible to student understanding.

We felt that repetition was important for student understanding of NOS, so we chose two NOS aspects to highlight for each laboratory; this allowed us to highlight each aspect twice through the course of the semester. For each laboratory, we created NOS learning objectives that explicitly stated what we wanted students to learn about NOS from the laboratory. We also created in-class discussion questions which were printed on overhead sheets and projected during the laboratory by the GTA. Students in ER laboratories also had an extra part to their post-laboratory assignment that asked them to incorporate an explanation of an NOS aspect in their laboratory report. An example of this implementation is provided in Table 10.2.

Incorporating assessment of NOS understanding into the grading scheme for the laboratory, however, was difficult. Because of the nature of the research design, four different versions of the laboratory were being implemented simultaneously, yet the grading scheme for the laboratories had to be the same. Students in ER laboratories discussed NOS, and their participation in those discussions was factored into their overall laboratory participation grade, but this was only a minor portion of their laboratory grade. Students in ER laboratories also had to address an NOS aspect or two in their laboratory reports. However, these student responses were graded as “complete/incomplete” because of the difficulty of creating a rubric that could be used uniformly by the GTAs. GTAs were, however, encouraged to comment on student NOS explanations.

Table 10.2 Examples of NOS objectives, discussion questions, and written reflection questions

Lab topic	NOS aspects	NOS objectives	Example discussion questions	Written reflection questions
Invertebrate biodiversity (ecology and biodiversity)	• Creative • Tentative • Inference	• To discover that scientists use inference, guided by creativity, to devise models (e.g., biodiversity indices) that explain natural phenomena • To explain the role of models in explaining natural phenomena • To recognize that new models can be proposed as the amount and quality of data improves or as a result of reinterpretation of existing data	1. Is it possible to come up with a sampling procedure that can fully represent the diversity of an area? 2. Why do you think scientists have several models to explain biodiversity? Is one biodiversity index (model) better than another? 3. Is creativity involved in the development of models? If so, how? 4. Is new data required to alter a model?	Reflect on the role of models such as biodiversity indices in science – why do we need models for biodiversity and why do we have so many different models?

GTA Preparation

Prior to implementation, the project team delivered a 2-day workshop to GTAs to prepare them to implement one of the treatment laboratories. Since GTAs were not assigned to their treatment until day two, all GTAs were trained in all instructional aspects, but asked to deliver their laboratory as instructed for that treatment.

The first day of the workshop included the introduction of the GTAs and professors who would teach the lectures, and discussion of the logistics of the introductory biology lectures and laboratories. A demonstration of an inquiry laboratory was done by a faculty member, with students as participants. A brief summary of NOS was also provided. Since laboratory assignments had to be made on day two of the workshop, GTAs turned in their preference for the type of laboratory they would want to teach at the end of day one. On the second day of the workshop, GTAs participated in an inquiry-based activity that modeled how to lead inquiry-based laboratories and performed activities developed by Lederman and Abd-El-Khalick (1998) (e.g., tricky tracks and black box activities) to generate discussion of the NOS aspects that would be emphasized in the laboratories. At the end of the workshop, GTAs were informed about their teaching assignments for the semester. Many GTAs were willing to lead the ER sessions, and although some were specific about not wanting to lead an inquiry laboratory, many said they would try either type of laboratory. Because of this flexibility, we were able to assign GTAs to treatments they requested, and did not have to assign anyone to a treatment they had stated they would not like to teach. Fifteen of the GTAs taught two laboratory sections that were the same treatment combination, and two GTAs taught one lab and also served as the "head TA" for either the inquiry or expository laboratory treatment.

Throughout the semester, GTAs attended laboratory preparation sessions that were specific to their laboratory type (inquiry or expository). GTAs who were assigned to ER sections then attended additional laboratory preparation sessions for delivering this portion of the laboratory. These sessions were necessary because most of the GTAs were not familiar with NOS and they needed to discuss and explore each aspect themselves before they could lead student discussion about them in a laboratory. We discovered that GTAs also needed training in how to facilitate discussion in their laboratories. As mentioned in the introduction, university science laboratories do not typically foster student discussion, so GTAs were unfamiliar with directing this type of instruction. We shared ideas with GTAs about how to get students to talk to each other, and how to ask questions to draw student ideas out without giving them a correct answer. In many cases, GTAs tried new techniques and then shared their experiences about what worked and didn't work in their classrooms with each other at the ER preparatory sessions.

Project Results

Data Collection

Both qualitative and quantitative data were collected to evaluate the effectiveness of the laboratory treatments. Undergraduate students and GTAs were asked to complete two pre- and post-assessments of their NOS understanding. One of the assessments consisted of 12 forced-choice items from the 113-item Views on Science-Technology Society, or VOSTS (Aikenhead, Ryan, & Fleming, 1989). All 12 items focused on the NOS aspects addressed in the laboratories. A second assessment instrument, the modified Views of Nature of Science, Form B (VNOS-B; Bell, Blair, Crawford, & Lederman, 2003), includes six open-ended questions from the VNOS-B (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002) and two additional questions designed to assess understanding of scientific inquiry.

Classroom observations and interviews were conducted to document the project implementation and capture the perception of the participants. Each GTA was observed teaching their class two to four times over the semester to document the fidelity of laboratory and ER implementation and to characterize their classroom practices. GTAs were also interviewed toward the end of the semester to capture their perceptions of the implementation. In addition, student interviews were also conducted to probe student perspective on the laboratories.

At the end of the semester, surveys were distributed to GTAs and students to capture their thoughts about the laboratories and what they learned. GTAs who participated in the ER laboratories were sent an online survey that asked them to reflect on their experiences with the GTA training meetings, their implementation of the ER approach, and their perception of the effectiveness and importance of the ER approach in teaching NOS in introductory biology laboratories. Undergraduate students filled out end-of-semester evaluations that asked them to rate (on a scale from 1 to 5) how much they learned about content, experimental design, laboratory techniques, nature of science, and writing a laboratory report.

What Students Learned from the Project

Analysis of the pre- to post-semester change in NOS understanding (VNOS-B and VOSTS; analyzed by a mixed model ANOVA incorporating the random effect of "lab section within treatment combinations") showed that the only statistically significant gain in NOS understanding was for students who participated in the ER laboratories, and only for the VNOS-B instrument. Overall, students gained NOS understanding from pre- to post-semester, particularly those in ER and E + ER. However, there were no instances of students in I + ER laboratories having statistically significant gains in NOS understanding from pre- to post-semester.

Undergraduate students also gained an understanding about certain aspects of NOS. According to VOSTS, student understanding became more appropriate for one question related to the tentative NOS for interactions between the inquiry and

ER treatments (E + ER students had the highest gains). Analyses of 200 randomly selected student VNOS-B responses found that students who participated in ER laboratories gained an understanding of the creative NOS and the myth of the scientific method, but only students in expository laboratories gained an understanding of the tentative NOS.

When students were asked to self-report how much they felt they learned about different learning outcomes of the laboratories, students in ER laboratories self-reported learning significantly more about NOS than students in other laboratories. Students in inquiry laboratories self-reported learning significantly more about experimental design than students in other laboratories.

We also tested student content understanding and their perception of instructional practices. A limited set of common mid-term and final laboratory questions were created and inserted into each laboratory exam. For both exams, students in expository sections performed better on those questions than students in the inquiry sections. Regarding instructional practices, students in inquiry and ER sections were more likely to say they used data to justify their responses and that they designed activities to test their own ideas than those in other sections. Students in ER sections were more likely to say they considered alternate explanations than students in non-ER sections. Students in inquiry sections were more likely to consult one another as sources for their learning and talk to one another to promote learning.

What GTAs Learned from the Project

Overall gains in NOS understanding for GTAs (as analyzed via ANOVA) did not vary by treatment for either VOSTS or VNOS-B. GTAs who taught ER laboratories had pre- to post-semester gains on one VOSTS question related to creativity/inference, and those who taught non-ER laboratories gained pre- to post-semester on the tentative NOS according to VNOS-B.

Observation and Interview Results

Based on the classroom observations, we found that fidelity of the inquiry and expository laboratory treatments were maintained by the GTAs. Students in inquiry classrooms were observed discussing experimental designs and analysis of their data. Although there was variability in the types of questions GTAs used to direct student learning, they rarely gave students the answers. The main difference in questioning was between GTAs who answered all student questions with "what do you think?" versus those who asked questions that refocused student discussion. In expository classrooms, students were observed to follow the directions that were imparted in the laboratory manual, and GTAs answered questions about the protocols or data analysis directly.

Given these differences in how the inquiry and expository classrooms functioned, we were interested in whether the ER implementation would be different between the two treatments. Almost all of the NOS discussions occurred at the conclusion of the inquiry or expository laboratory activities. There was often a physical transition in the classroom, as students cleaned up their benches and the GTAs placed the NOS discussion questions on the overhead projector. We found that once this transition occurred, both inquiry and expository classrooms implemented the ER sessions in roughly the same manner.

GTAs usually spent the last 5–10 min of the laboratories discussing NOS. Online surveys confirmed this observation, with one GTA reporting an average of 10-min discussions, two GTAs reporting 8-min discussions, three reporting 5-min ones, and 1 reporting only a minute's discussion. Observations also identified that GTAs did not insert NOS conversations into the laboratory activities. In two cases, two different GTAs referred to the difference between observation and inference during a laboratory, but those were the only recorded instances of this occurring. Although we did not explicitly tell GTAs to address NOS throughout the laboratory, we encouraged them to make connections when possible, and perhaps insert some of the discussion questions throughout the laboratory. GTAs, however, chose to temporally separate the laboratory activity from the NOS discussions.

Observations and online surveys also identified that GTAs led discussion about NOS in three main ways: (1) GTA-led, (2) student-led, and (3) student small groups. In GTA-led instruction, the GTA read the NOS discussion questions one by one and asked for student volunteers to give answers. In most classes, this method resulted in a few individuals answering most of the questions, and little discussion. In student-led discussions, the GTA would pick a student volunteer who would be the discussion leader for the day. The GTA would typically stand at the back of the classroom and let the student control the discussion, only interrupting with comments as necessary. In student small group discussion, the GTA would give small student groups time to discuss each NOS question prior to asking for answers. Most GTAs started the semester with GTA-led discussions, and then a few transitioned to student-led or student small group as the semester progressed. On average, GTAs reported that less than 50% of their students were volunteering answers to the NOS discussion questions.

GTA rapport with their students and ability to lead discussions was found to be a large factor in how the ER sessions were implemented. Those GTAs who, during the laboratory activities, moved around the classrooms, fostered informal conversations with their students, asked intellectually stimulating questions, and were willing to try different discussion environments also fostered more productive NOS sessions. GTAs who appeared nervous, had a difficult time interacting with students, lacked the skills to question effectively, and exclusively used a GTA-led instructional approach typically had a more difficult time directing NOS conversations in meaningful ways. Their students sat silently, knowing the GTA would either answer the question for them, or give up and end lab. In some cases these GTAs who had difficulty leading discussions were organized teachers who could communicate scientific concepts; what they lacked was the ability to foster discussion among their students.

Beyond the differences in the GTAs' ability to foster discussion, however, we observed a general failure to foster student understanding about NOS. Although GTAs were not grading student NOS understanding, they were supposed to encourage student discussion about the topic and help students gain different perspectives about it. We didn't want students to feel that GTAs were seeking a correct answer to the questions, although we did provide the correct interpretation of the aspect in the NOS objectives for the laboratory. We believed that this written guidance, in addition to encouraging discussion and exposing students to different ideas of their classmates, would help them develop more appropriate understanding. However, we observed that GTAs did not encourage students to respond to other students' contradictory responses. They accepted all answers and rarely challenged an idea or asked students to elaborate on their answers. None of the GTAs provided a closing explanation of the appropriate views of the targeted NOS aspects.

Only one GTA fostered reflective classroom discussions on NOS. Although he allowed all students to express their views, he asked follow-up questions of the student when a naïve view was expressed and tried to lead the student toward an informed view. In some cases, students revisited their views and changed their answers as a result of this technique. For instance, while discussing creativity in one laboratory, a student stated that creativity did not have a place in science. After questioning from the GTA and discussions with the class, the same student acknowledged that creating scientific models requires creativity. This GTA also used different examples from the ones mentioned during the weekly ER preparation meetings, which indicated that he understood the NOS aspects and was prepared to discuss them with the students.

Interestingly, GTAs did not recognize the limitations of their instructional abilities in leading the ER sessions. The end-of-semester survey asked GTAs to reflect on their perceptions of the ER part of the laboratories. They expressed that the ER preparation sessions adequately prepared them for the ER discussion sessions. Their only complaints were that they felt rushed doing the discussions at the end of the class period, and that students were not interested in learning about NOS, which they felt affected the quality of the discussions.

What Did We Learn by Doing This Project?

There were many enlightening moments during this study, both from the standpoint of management of a curriculum revision project, and from the perspective of student learning about NOS. In reviewing the project, we have chosen three factors that we would pay closer attention to if we had to do the study over again.

Appropriate professional development of GTAs is important. In many previous studies on ER, instructors who implemented this approach had informed views of NOS, valued the teaching and learning about NOS, and were already expert teachers. However, even teachers who have informed understanding of NOS have a difficult time inserting explicit discussions of NOS into their classrooms (Abd-El-Khalick, Bell, & Lederman, 1998; Akerson & Abd-El-Khalick, 2003; Lederman, 1999). The GTAs in our study had limited teaching experience, if any at all, and had never learned about NOS explicitly. Despite this, we found that creating NOS discussion sessions that GTAs were comfortable implementing was possible. However, our observations suggest that the GTAs may only have felt at ease because they did not feel an imperative to direct students to a specific NOS understanding. Although it is possible that GTAs with more informed NOS understanding may have been more effective at directing student understanding of NOS, we also believe that a GTA's ability to connect with students and foster meaningful discussions that lead to learning is of primary importance.

Therefore, the results make clear that GTAs need to know that student NOS understanding is the most important outcome of ER sessions, and GTAs need to be given the tools to understand the value of classroom discussion in that process. As recommended by other teacher education scholars, the role of the teacher is to not only encourage student discussion and reflection, but also to engage and challenge students to expand their ideas and think more deeply about the topic at hand (Van Zee & Minstrell, 1997). GTAs must not be afraid to redirect student ideas and take a more active role in shaping the conversations during ER sessions.

To support student learning, colleges and universities need to not only train GTAs better (Luft et al., 2004) but also match the nature of the training to the learning outcomes that GTAs will be expected to foster. For our project, professional development activities should have focused on developing GTA abilities to foster and guide discussions in which students make meaning from their laboratory experiences. This would not only have supported GTAs in the ER sessions, but would have supported them in fostering student learning from both inquiry and expository laboratories as well.

Variation among the learning outcomes and expectations is problematic. One struggle we encountered before, during, and after the project was a lack of uniform understanding of the learning outcomes of the laboratories. In some cases these battles were explicit, and in some cases they were implicit "hidden curriculum."

We believe that students' perception of the value of learning about NOS impacted their participation in the class discussions. Student conception of science centers around content and process skills, and they are not inclined to value NOS learning unless it impacts their course grade. Although we made explicit to students that NOS understanding was an outcome for the laboratory, their level of effort toward this learning objective was often correlated to the laboratory points they were receiving for that effort. GTAs reported that students participated more willingly in the ER discussions once they realized they would have to discuss the NOS aspects in their laboratory reports.

We also failed to appreciate the strength of the implicit goal of technical writing skills that the assessment by laboratory reports put on the course. When we compiled the final student evaluations, we found that students rated learning about how to write a laboratory report as the most important thing they learned in the course, regardless of the type of laboratory they participated in. Our expectation was that when students wrote laboratory reports, they would use them as an opportunity to highlight their understanding of the theoretical background, methods, data analysis, data interpretation, and research implications of the laboratory activity. What we did not recognize was that almost all the GTAs were grading the laboratory reports based on technical writing proficiency such as appropriately labeling report sections, labeling figures and tables, using correct tense and scientific tone, and citing references correctly. Although these skills are important in laboratory reports, they were essentially the only standard by which the reports were being graded. And since the laboratory reports were a major portion of the laboratory course grade, these proficiencies were what students thought were the main learning outcome of the laboratory. In retrospect, we should have provided more assistance to GTAs in matching their grading of the laboratory reports with the stated learning outcomes of their laboratory treatment.

Despite the goal of the curriculum revision being focused on NOS, there was a constant subset of faculty members affiliated with the course who thought the main focus of the laboratories should be content and technical skill. Many faculty had the perception that the laboratory would be able to successfully convey multiple primary learning objectives, and that NOS was just being added to the already long list of learning objectives. These divergent perceptions of what was most important for students to learn affected the perception of the success of the project after the results were reported. The project team was pleased overall because of the NOS and inquiry learning outcomes, but when other faculty members saw that students in expository laboratories performed better on the content questions, they assumed that the revision was not successful. To them, a decline in content learning was not balanced by the learning gains of students in experimental design, or NOS understanding.

In hindsight, we should have done a better job of clarifying and justifying the laboratory learning objectives to everyone affected by the project. We did not anticipate faculty members outside of the project team becoming concerned about the revision, because they had typically taken limited interest in the laboratories prior to the revision. We should have discussed advocating for the project when we met with the advisory board, and gathered their recommendations for informing stakeholders about the project. Several of the advisory board members are well-known scholars in NOS, inquiry, and in their respective scientific fields, and we could have asked them to meet with others at the university or present workshops or seminars to foster a better understanding of the rationale behind the project.

We also needed to do a better job of considering how students should be assessed and graded in the course, based on the new laboratory goals. The writing of laboratory reports was a traditional focus in the course, but there needed to be a reconsideration of what students should discuss in the laboratory report and how they are graded. Clearly, NOS also needed to be included in the course assessment, both to help students focus on it as a learning outcome and also to help GTAs understand the importance of it as a student learning outcome.

Integrating NOS into curriculum needs to be done with care. We have come to understand that the construct of NOS is much more complicated than we thought prior to the project. NOS understanding was not facilitated uniformly, rather certain aspects were affected by only certain treatments. For our project, undergraduates in expository laboratories or E+ER laboratories tended to gain an understanding of the tentative NOS, but GTAs in either inquiry or expository laboratories, but who were NOT teaching ER, gained in tentative NOS. Both undergraduates and GTAs experiencing ER laboratories made gains in understanding the creative NOS, but only undergraduates in ER laboratories gained an understanding of the myth of the scientific method.

Thus, we would suggest a cautionary note to those who are considering focusing broadly on increasing NOS understanding in students. Our results suggest that individual laboratories should focus on individual NOS aspects, and that the pedagogy of the laboratory experience should be built around that aspect, versus adding the aspect to a precreated uniform type of laboratory. More research needs to be undertaken to identify what types of laboratories and discussions are successful for specific NOS aspects. It also means that those wishing to integrate ER into laboratories will need to devote more time to the thoughtful planning of the ER portion of the laboratory relative to the time spent in developing the actual activity. We believe that the type of discussion that the laboratory facilitates may be just as important as the activity itself.

The importance of the NOS discussions was also affected by its temporal placement in the laboratory. By placing the ER discussions at the end of sessions, with students eager to get the discussions “done with” so they could leave, we were sending a message that NOS was an after-thought. One alternative is to weave the NOS discussions throughout the laboratory activities. This has the advantage of making it a clear part of the course and not an “add-on.” The other alternative is to give students discussion questions at the end of laboratory that they will discuss at the beginning of laboratory the next week. This would give students time to consider the aspects prior to discussing them. Either way, NOS needed to be a more structured part of both the laboratory curriculum and the assessment.

Concluding Thoughts

This study has several implications for those wishing to integrate NOS instruction into college science courses. One is that understanding of NOS, and not just discussion of NOS, must be a clear goal to both GTAs and students. This requires a more complete integration of NOS learning into the curriculum than just ungraded discussion and modules, and more assistance in training GTAs to foster student learning about NOS. The focus for NOS learning should also be on individual aspects, and different types of laboratory learning experiences may need to be designed for each NOS aspect.

Too often, in undergraduate science classes we assume students learn through the simple task of completing the laboratory or assignment, and certainly this is reflected in many laboratories students participate in today (Hofstein & Lunetta, 2004). As educators, we need to spend more time crafting the learning outcomes we expect to see from laboratory experiences, more time helping instructors understand how to appropriately foster these learning outcomes, and more time encouraging student discussion about their laboratory experiences to foster learning.

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Chapter 11
Beyond Understanding: Process Skills as a Context for Nature of Science Instruction

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What distinguishes science from religion, history, and other ways of knowing? What makes science *science*? The answers to these questions form the basis of the nature of science and are fundamental to science education. Understanding the characteristics of science supports the development of science literacy (National Research Council, 1996) and helps students recognize both the strengths and limitations of scientific knowledge (Bell, 2008).

Despite the many potential benefits associated with appropriate nature of science understandings, K-12 students in general hold many alternative conceptions about science. Teachers, as well, possess a variety of misconceptions about science, and find the nature of science to be both abstract and difficult to teach. To tackle these problems, we explore the literature related to nature of science instruction and then describe an instructional approach that shows promise in facilitating teachers' understanding and abilities to teach about the nature of science. The process skills-based approach guides teachers to recognize where the nature of science can fit into the science curriculum and provides a framework for addressing the nature of science in ways that are informed by situated learning theory. Finally, we provide an overview of three investigations into the efficacy of using the process skills-based approach to help preservice teachers develop appropriate conceptions of the nature of science and to facilitate their instructional practice.

Rationale for Teaching the Nature of Science Through Process-Skills Instruction

Understanding the nature of science supports the development of scientific literacy (National Research Council, 1996), general reasoning skills, socioscientific decision making, and appreciation for the major accomplishments of science (Driver, Leach, Millar, & Scott, 1996). The nature of science also helps to place science

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content in the broader context of science, representing generalizations of what science is as well as the characteristics of scientific knowledge. These overarching understandings of the nature of science represent core issues associated with science and science education. As such, the nature of science is a fundamental concept to explore in science at all grade levels (National Research Council, 1996).

While there are varied ways to define the nature of science, most science education research converges on a core set of nature of science tenets appropriate to teach K-12 students (as well as preservice and in-service teachers). The original set of nature of science tenets described by Abd-El-Khalick, Bell, and Lederman (1998) have been reinforced by subsequent research, including a Delphi study (Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003) and a comparison of standards documents from around the world (McComas & Olson, 1998). This general agreement is reflected in national and international science education standards documents (Lederman, 2007) that highlight the following core nature of science understanding:

- there is no single scientific method
- scientific knowledge is empirically based, tentative, subjective (theory-laden), and comprised of both observations and inferences
- scientific theories and laws serve very different, noninterchangeable functions
- creativity plays an important role throughout the scientific process
- science is socially and culturally embedded.

Teaching and Learning About the Nature of Science

Implicit Vs. Explicit Instruction

Research over the last four decades has yielded two primary instructional strategies for teaching the nature of science to students, the implicit and explicit approaches (Lederman, 1998). The implicit approaches are based on the assumption that students will develop accurate conceptions of the nature of scientific inquiry and knowledge as a natural byproduct of learning about scientists' work in the past (Lawson, 1982) or by participating in authentic scientific investigations (Akindehin, 1988; Bell, Blair, Crawford, & Lederman, 2003). In contrast, explicit approaches intentionally draw students' attention to targeted aspects of the nature of science through discussion, reflection, and specific questioning.

Research indicates that implicit nature of science instruction through teaching the history of science or through doing science (e.g., scientific inquiry) is not consistently effective in improving students' conceptions of the nature of science (Abd-El-Khalick & Lederman, 2000a; Bell et al., 2003; Khishfe & Abd-El-Khalick, 2002). In particular, research indicates that teaching the history of science without explicit nature of science instruction does not seem to impact learners' nature of science views (Abd-El-Khalick & Lederman, 2000a; Solomon, Duveen, Scot, & McCarthy, 1992). Similar lackluster results are associated with teaching the nature of science implicitly through learners doing science. For example, Bell et al. (2003)

studied the nature of science conceptions of high school students involved in an 8-week scientific research apprenticeship. This research experience involved no explicit nature of science instruction. In fact, one participating mentor scientist remarked that his students would learn about the nature of science by “osmosis.” However, this anticipated implicit learning did not materialize. The majority of students showed no improvement in their nature of science conceptions, despite substantial gains in their understanding of the particular process skills they performed as part of their respective research projects.

Alternatively, research has demonstrated that explicit nature of science instruction can be effective in developing appropriate conceptions for students of all ages (e.g. Abd-El-Khalick et al., 1998; Hanuscin, Akerson, & Phillipson-Mower, 2006; Khishfe, 2008; Scharmann, Smith, James, & Jensen, 2005; Schwartz, Lederman, & Crawford, 2004). For example, in a study that directly compared implicit and explicit inquiry approaches to nature of science instruction, Khishfe and Abd-El-Khalick (2002) investigated sixth graders’ nature of science understanding before and after a 2.5-month intervention. Students who experienced the implicit instruction retained their initial conceptions about the nature of science. In contrast, those students who experienced the explicit instruction exhibited improved nature of science views.

In a noncomparative study of elementary preservice teachers and undergraduate teaching assistants, explicit nature of science instruction within a physical science content course substantially improved participants’ nature of science conceptions (Hanuscin et al., 2006). Other studies involving preservice teacher participants had similar successes in improving nature of science understanding through explicit instruction (e.g., Lin & Chen, 2002; Scharmann et al., 2005; Schwartz et al., 2004). In-service teachers also have been shown to improve their nature of science views with extended professional development involving explicit instruction on the topic (i.e., Akerson & Hanuscin, 2007).

Thus, a broad range of studies indicate that explicit instruction holds substantial potential to shape appropriate conceptions of the nature of science. Further, explicit instruction can be placed within a variety of scientific contexts or be the focus of the lesson itself, with no direct links to specific science content. This raises an interesting question with practical implications. What role does context play in facilitating the development of appropriate nature of science conceptions? The following section reviews a subset of investigations utilizing explicit approaches to nature of science instruction that have explored the impact of context on nature of science instruction and learning.

Context and Nature of Science Instruction

Situated learning theory (Lave & Wenger, 1991) asserts that context matters in any instruction and that learning is enhanced when it is embedded in a context similar to that in which it will be applied. Therefore, students may learn the nature of science more effectively when it is linked to an authentic and relevant context. When connected to scientific contexts, nature of science instruction can provide practical applications of nature of science tenets. The context provides an appropriate setting and reinforces what students need to know about the nature of science.

In response to the promise of contextualized instruction, researchers have evaluated nature of science instruction in multiple contexts including scientific content (i.e., socioscientific issues) and engaging in scientific inquiry. For example, Khishfe and Lederman (2006) compared ninth grade student outcomes when nature of science was taught in the context of global warming versus as a stand-alone topic. Students in both groups exhibited improvements in appropriate nature of science conceptions, therefore the interventions were judged as equally effective. Matkins and Bell (2007) also integrated nature of science instruction with global climate change content, but in an elementary science methods education course. The preservice elementary teachers in this study both improved their nature of science views and were able to apply their understanding to socioscientific issue decision making.

In a follow-up investigation, Bell, Matkins and Gansneder (2011) compared gains in preservice elementary teachers' understanding when nature of science instruction occurred within the context of global climate change versus as a stand-alone topic. Teachers participating in explicit nature of science instruction showed statistically significant gains in appropriate conceptions regardless of whether that instruction was embedded in the context of global climate change. The teachers not only learned about the nature of science and global climate change, but were also able to apply their understanding to justify energy policy.

Integrating nature of science instruction within the context of scientific inquiry has met with success in cases where reflection and discussion are emphasized (Scharmann et al., 2005; Schwartz et al., 2004). Reflection can be encouraged through techniques such as reflective journaling or discussions (e.g., Bell et al., 2003). Schwartz and colleagues (2004) found that reflection played an important role in developing appropriate nature of science conceptions among preservice teachers during research internships. While most preservice teachers showed some gains in nature of science conceptions, those preservice teachers who embraced reflection were most successful in improving their understanding of the nature of science.

In general, research indicates that explicit nature of science instruction can support students' development of more appropriate views regardless of whether it is taught as a stand-alone topic or integrated into a scientific context. But what about learners *using* their nature of science understanding? Research suggests that understanding the nature of science is necessary but insufficient for teachers to integrate the nature of science into their own instruction (Akerson & Abd-El-Khalick, 2003; Bell, Abd-El-Khalick, & Lederman, 1998; Lederman, 2007). There is some indication that learning about the nature of science within particular science contexts may have the added benefit of supporting learners' application of nature of science conceptions to novel situations, including teaching (Bell, Binns, Schnittka, & Toti, 2006; Binns, Schnittka, Toti, & Bell, 2007). Thus, the context in which nature of science instruction is situated may be more important when the goal is to encourage teachers to incorporate the nature of science into their own instruction. Bell (2008) has formalized a contextual approach utilizing science process skills as stepping stones to nature of science understanding and instruction. The following section describes the approach and provides examples of its utilization.

Description of the Process Skills-Based Approach

Science can be viewed as consisting of three interacting domains (Spector & Lederman, 1990). These domains may be viewed as a framework for science instruction designed to promote scientific literacy (Bell, 2008). Each of these domains represents a specific component of science that contributes to a holistic view of the scientific enterprise (Fig. 11.1). Science as a body of knowledge is the most familiar of these domains, as it includes the facts, definitions, and concepts typically found in science textbooks and focused upon in science classes. It is what we have come to know about the natural world through science. The second domain includes the processes and methods of science, which are commonly addressed through instruction

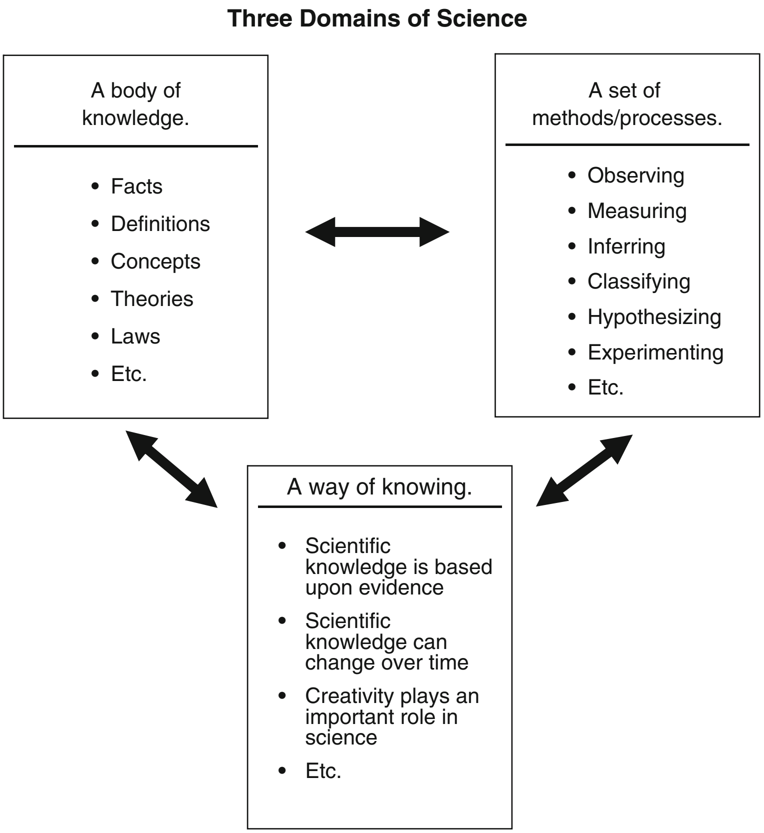

Fig. 11.1 Interplay of three domains of science

that focuses on laboratory activities, scientific inquiry, and skills development. It is how we use science to learn what we know about the natural world. Science as a way of knowing is by far the least familiar of the three domains. Also known as the nature of science, this aspect of the scientific enterprise focuses on the values, assumptions, and characteristics of scientific knowledge itself (Lederman, 1992). It describes science as a unique way of knowing about the natural world that includes specific qualities, such as the need for knowledge claims to be based on evidence and the recognition that such claims can change with new evidence. The nature of science is the least familiar and least taught domain of the scientific enterprise (Lederman, 2007).

The process skills-based approach to nature of science instruction seeks to improve nature of science instruction by connecting the less familiar nature of science concepts to the more familiar process skills (Table 11.1). In this approach, students learn about the nature of science and the scientific enterprise as they develop the skills necessary to do science (Bell, Maeng, Peters, & Sterling, 2010). The approach is consistent with situated learning theory, as abstract concepts of the nature of science are taught in the context of the more familiar science process skills. Students learn about science while doing science, with opportunities to explicitly reflect on what they have learned and its connection to the scientific enterprise as a whole. Thus, process skills serve as an authentic context for the nature of science instruction, helping to ensure that appropriate understandings are accessible to learners of all ages.

Table 11.1 Teaching the nature of science through process skills

Process skill	Nature of science tenet(s)
Observing	Scientific conclusions are based on evidence. They can change as new evidence becomes available. Scientific laws are generalizations that summarize observational data.
Inferring	Scientific conclusions involve both observation and inference. Scientific theories are partially based on things that cannot be observed directly, and hence are inferential.
Measuring	Many units and constants in science are decided by convention. They are not read directly from the book of nature.
Classifying	There is often no single “right” answer in science. Science is socially and culturally embedded.
Predicting/ hypothesizing	Scientific theories provide the foundation on which predictions and hypotheses are built.
Analyzing	There are always multiple ways to interpret data. Sometimes these multiple ways result in different conclusions.
Concluding	Scientific conclusions can be influenced by scientists’ background knowledge. Theories provide frameworks for data interpretation.
Designing experiments	There are many ways to do science. There is no single scientific method that all scientists follow.

Adapted from *Teaching the nature of science through process skills: Activities for grades 3–8* by R. L. Bell, 2008, p. 269. Copyright 2008 by Pearson Education, Inc.

In general, the process skills-based approach involves beginning each nature of science lesson with an activity designed to teach specific science process skills such as observation, inference, measuring, etc. At the conclusion of the activity, the teacher encourages students to explicitly reflect upon and discuss the nature of science in the context of the activity and associated process skills. The teacher uses questioning, associated feedback loops, and other scaffolding techniques to facilitate reflection on the nature of science and to promote appropriate nature of science conceptions. Throughout this process, the teacher is careful to delineate the nature of science as distinct from the process skills addressed in the lesson. We outline in the following section how a teacher might teach specific nature of science tenets related to the process skills of observation, observation/inference, measuring, and experimental design.

Process skills activities involving observation alone are perhaps the simplest way to link process skills instruction to nature of science instruction. The instructor begins the lesson by introducing to students the scientific definition of observation—using the five senses (often augmented with technology) to gather information about the natural world. Next, students are challenged to make careful observations about an object or image. As the students practice making observations, the instructor monitors their progress and offers suggestions for improving accuracy and clarity. Once it is evident that the students have mastered making observations, the instructor concludes the activity with a class discussion of their results, eventually leading students to reflect on the connections between the way the students made and used observations during the activity and the work of scientists. Specifically, the instructor links the activity to the concepts that observations are a type of scientific evidence, that scientific conclusions are based on evidence, and that scientific knowledge has an empirical base.

Activities in which students make observations and inferences can provide powerful contexts for teaching about the nature of science. Bell (2008) describes a wide variety of activities conducive to observation/inference lessons. In general, these lessons proceed similarly to those involving observation alone, but this time include instruction and opportunities for making inferences. The instructor takes care to be sure that students distinguish between observation and inference, both in defining the terms and in performing these skills during the activity. The concluding discussion explicitly addresses multiple nature of science ideas by connecting what students do during the observation/inference activity to key characteristics of scientific knowledge and how it is developed. For example, students' observations and inferences provide an ideal setting for discussing how scientific conclusions involve both observation and inference, and that science is more than the accumulation of observations alone. Students may also extend their classroom experiences with observation and inference to discuss how multiple inferences can often be supported by the available data. Additionally, students can reflect on how their inferences can change with new data, and that this "tentativeness" is applicable to science as well. Finally, the instructor can lead students to recognize that, while scientists cannot prove their inferences to be correct in an absolute sense, their goal is to develop plausible inferences that fit all of the available evidence.

Experimental design activities, in which students design an experiment to answer a research question, are another type of process-skills activity that can teach students important nature of science ideas. Experiments are scientific investigations in which a hypothesis is tested through manipulation of variables and measuring what happens because of the change. In experimental design activities, students first form a research question about a phenomenon. Students identify an independent variable, a dependent variable, and a method of measuring the dependent variable upon manipulation of the independent variable. Based on prior knowledge, observations, and research, students propose a hypothesis of the phenomenon's behavior under the experimental conditions. They conduct their experiment based on their experimental design and compile the results. Following the activity, the students discuss their results and the process the students used to collect their data. The instructor addresses how students developed their hypotheses, their experiment, and how their results confirm or dispute their hypothesis. The instructor then links these ideas to how scientists do their work and how scientific knowledge is developed. This discussion includes the following key ideas: scientific hypotheses are not just guesses but are based on research and observation; hypotheses can be disproven but can never be absolutely proven; experiments are a specific type of way scientists develop scientific knowledge; scientists use both experimental and observational methods to develop scientific knowledge and thus there is no single "scientific method"; and scientists engage in scientific inquiry in which they ask questions, collect, and analyze data using a variety of methods to answer these questions.

In these examples and any other activity taught using the process skills-based approach, the abstract nature of science tenets are discussed in the context of the activity and its associated scientific process skills. This context provides students with experiences on which to build new nature of science understanding. The nature of science is made relevant and meaningful to students through this process skills-based approach. Regardless of the particular scientific process skills incorporated in an activity, these process skills serve as the accessible and engaging context for explicit nature of science instruction.

Research Supporting the Process Skills-Based Approach to Teaching Nature of Science

We examined the efficacy of the process skills-based approach to nature of science instruction in preparing preservice teachers to teach nature of science in three separate studies. In the first study, we explored the effectiveness of the process skills-based approach in changing preservice science teachers' views of the nature of science. In the second study, we investigated how preservice teachers who experienced process skills-based nature of science instruction taught the nature of science during student teaching. In the third study, we followed a subset of the preservice teachers from the second study into their induction year to examine how they implemented nature of science instruction as beginning teachers.

First, we assessed the effectiveness of the process skills-based approach in changing preservice science teachers' views of the nature of science. Participants in this study were 7 male and 10 female preservice teachers enrolled in the first year of a 2-year Master in Teaching (M.T.) program at a large, mid-Atlantic university. The participants all held or were completing bachelor's degrees in their respective science content area at the time of the study. The first year of this program consists of a year-long science teaching methods course sequence that prepares preservice teachers to teach science. During this two-course sequence, professors employ the process skills-based approach as the primary means through which the preservice teachers learn about the nature of science and how to teach the nature of science. Prior to any nature of science instruction, we assessed the participants' initial knowledge of the nature of science using the modified *Views of the Nature of Science* (VNOS-B) questionnaire (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002).

We analyzed the data by coding each participant's responses to the questionnaire using *a priori* codes derived from the nature of science literature (e.g. Lederman, 2007). Thus, codes corresponded to the nature of science tenets that scientific knowledge is empirical, tentative, creative, subjective, the product of observation and inference, is developed using many methods, and that scientific laws and theories constitute different kinds of knowledge. Each of these codes was further subdivided into alternative, transitional, or informed (Lederman et al., 2002; Khishfe & Lederman, 2006). These labels represent a judgment on the relative appropriateness of a coded statement with respect to a particular nature of science tenet. For example, a statement coded "tentative-alternative" represented a noninformed view of the tentative nature of scientific knowledge. This view was likely an extreme view that either scientific knowledge is absolute or completely changeable and not very worthwhile. Statements coded "tentative-informed" represented statements in which a participant acknowledged that scientific knowledge is not absolute and can change with adequate supporting evidence or with new perspectives on existing data. Statements that expressed incomplete but appropriate views reflected emerging understanding of the tentative nature of science and were coded "tentative-transitional."

The results of this analysis indicated that these preservice teachers held many alternative conceptions about the nature of science. In fact, most had alternative views on the majority of the tenets (Table 11.2). For example, all participants held the common misconception of a hierarchical relationship between theories and laws. In general, the participants viewed theories as less certain than laws and many explicitly noted that theories become laws once enough evidence has been collected to support them. Additionally, participants overemphasized the role of experiments in developing scientific knowledge. Most participants associated all scientific progress with experimentation even though much scientific knowledge is created using other methods. Many also noted that scientists can be dishonest or make errors and these are common reasons underlying scientists reaching different conclusions, an overly negative view of subjectivity in science. It was evident that, despite the fact they had completed their science coursework for their majors, these preservice teachers were not ready to effectively teach the nature of science to their own students.

Table 11.2 Categorization of participant's responses prior to instruction

Nature of science tenet	Alternative	Transitional	Informed
Scientific knowledge is			
Empirical	9	8	0
Tentative	12	4	1
Creative	12	5	0
Subjective, theory-laden	8	9	0
Roles of observation, inference	4	12	1
Relationship between theories and laws	17	0	0
Social and cultural influences	14	3	0
No single scientific method	12	4	1

Throughout the science teaching methods course sequence, the process skills-based approach to nature of science instruction was modeled and explicitly taught to participants. A summary of a subset of activities used in the courses and the targeted nature of science conceptions are described in Table 11.3. Through these activities, preservice teachers were explicitly taught how to teach the nature of science to their students by linking process skills instruction to specific nature of science tenets.

On the last day of the science teaching methods course sequence, the preservice teachers again completed the modified VNOS-B questionnaire. Then we interviewed them regarding their responses to both the pre- and post-questionnaires. The goal of these semi-structured interviews was to validate our interpretation of their questionnaire responses and to explore the degree to which preservice teachers' nature of science views changed. During the interview, participants were encouraged to clarify and elaborate on their responses to the questionnaires. Questions also addressed whether participants believed their views had changed pre- to post-instruction and why. We classified participants' post-instruction views on each nature of science tenet as alternative, transitional, or informed based on their questionnaire and interview responses, as previously described.

Post-instruction, we found participants' responses shifted substantially toward more informed views of the nature of science. Overall, there were large gains in informed views for each of the assessed nature of science tenets (Table 11.4). Almost every participant demonstrated gains in understanding on every nature of science tenet. In particular, all participants shifted away from the absolute statements that were common prior to instruction, recognizing that all scientific knowledge can change. These preservice teachers moved beyond the misconception that science is absolute without erring too far on the side of science always changing. Additionally, most participants gave creativity an essential place in science. Post-instruction responses included a substantial expansion of where and how creativity is part of science, to all aspects of experimentation and beyond to any scientific problem solving and data interpretation. All of the preservice teachers expressed that there is no single scientific method and expanded views of the roles of observation and inference in the construction of scientific knowledge. Additionally, almost all participants dismissed their initial conception that scientific theories become

Table 11.3 Example activities used in the science teaching methods course to teach the nature of science through process skills instruction

Activities	Nature of science tenets
Mystery Tube (Olsen & Loucks-Horsley, 2000): Students observe anomalous behavior of the tube and infer the hidden mechanism. **Mystery Cans** (Bell, 2008): Students observe anomalous behavior of liquid moving between two cans and infer the hidden mechanism. ***Oobleck*** (Sneider, 1985): Students investigate the properties of a substance through observation. From observations, students develop a "law" to describe the behavior of *Oobleck*. **Fossil Footprints** (Olsen & Loucks-Horsley, 2000): Students observe a series of images. For each image, they make observations and inferences. They revise their inferences as they gather more evidence, in the form of observations of the next image in the series. **Mystery Cookies** (Bell, 2008): Students make indirect observations of the inside of a cookie, then infer what is hidden in the cookie. They eat the cookie and modify their inferences based on these new observations.	Human observation, inference, and imagination play a role in the development of scientific knowledge. Scientists use creativity and imagination to interpret incomplete evidence. Scientific knowledge is tentative. Scientific laws are inherently different from scientific theories. Observation and inference contribute to the development of scientific knowledge. Scientific knowledge may change with new observations.
Stopper/Popper (Karplus & Thier, 1967): Students explore the behavior of a "stopper/popper" through an observational investigation.	The experimental method is one way (but not the only way) of doing science.
Fossil Fragments (Bell, 2008): Students make a drawing of a fossil fragment. They then infer the rest of the organism from which the fossil was obtained and that organism's habitat and explain how their inferences relate to their observations of the fossil. They compare this to the work of paleontologists and compare their process to the steps of the scientific method.	Prior knowledge plays an important role in developing inferences. Scientists use creativity and imagination to interpret incomplete evidence. There is no single "scientific method."

scientific laws when proven and clarified that theories provide scientific explanations for natural phenomena. As evidence of further improvement of their nature of science views, almost all participants implied or explicitly described ways that society and culture influence science. For example, one preservice teacher pointed out that scientists influence each other as does a person's education, experiences, and religion. Others expressed that scientific knowledge does not exist in a vacuum and that preferences for new ideas and different styles of interpreting data can change with societal trends.

Explicit, reflective instruction through the process skills-based approach resulted in a substantial increase in the number of participants with informed views of the nature of science. Further, preservice teachers' interview responses suggested they attributed their new nature of science understanding to the nature of science

Table 11.4 Preservice teachers' conceptions of the nature of science following instruction

Nature of science tenet	Alternative	Transitional	Informed
Scientific knowledge is			
Empirical	0	0	17
Tentative	0	4	13
Creative	0	7	10
Subjective, theory-laden	0	4	13
Roles of observation, inference	0	3	14
Relationship between theories and laws	0	1	16
Social and cultural influences	1	8	8
No single scientific method	0	2	15

instruction they experienced during the science methods course sequence. Thus, preliminary results of this study indicate that the process skills-based approach can be very effective in helping preservice teachers develop more appropriate nature of science conceptions.

Clearly these preservice teachers learned about the nature of science, but would they use their new understanding to teach the nature of science in the classroom during student teaching? To answer this question, we conducted a follow-up study on a second cohort of preservice science teachers enrolled in the same 2-year M.T. program. These 10 female and 4 male preservice teachers completed the same science teaching methods course sequence that incorporated the process skills-based approach to nature of science instruction. We chose not to preassess this cohort of preservice teachers regarding their views of the nature of science, as the results of the previous study corroborate an extensive body of literature, which indicates preservice teachers hold many alternative conceptions of the nature of science (e.g., Abd-El-Khalick & Lederman, 2000b; Abell & Smith, 1994; Akerson, Abd-El-Khalick, & Lederman, 2000; Gallagher, 1991; Lederman, 1992). Further, the purpose of the second study was to see if participants would teach the nature of science. Thus, we wanted to avoid overemphasizing nature of science assessment, which could alert participants to the goal of our research. All we needed to know was that these preservice teachers possessed adequate conceptions of the nature of science prior to their student teaching semester, not what their conceptions were prior to enrolling in the program.

On the final day of the science teaching methods course sequence, we assessed their conceptions of the nature of science with the modified VNOS-B questionnaire. These post-assessment results were similar to those described in the previous study. All of the participants expressed that scientific knowledge is both empirical and tentative and held informed conceptions of the role of observation and inference in the development of scientific knowledge. Accordingly, these preservice teachers recognized the difference between observation and inference and that scientific knowledge is based on both observation and inference. The majority of the participants also expressed informed views of the other five tenets of the nature of science assessed by the VNOS-B. Further, responses to the VNOS-B questionnaire and interview prompts indicated they understood that scientific knowledge is ultimately based on empirical evidence and that all scientific knowledge, including scientific theories and laws, is subject to change through the acquisition of new data or through new interpretations of existing data. All of the 14 participants were classified as having either transitional or informed understanding of the individual tenets of the nature of science, suggesting that they had developed sufficient understanding of nature of science to allow them to teach appropriate conceptions of the nature of science to their students (Table 11.5). The question was then what would these preservice teachers, who learned about the nature of science through the process skills-based approach, do with their new knowledge while teaching students?

After completing the science teaching methods course sequence, each preservice science teacher completed a semester-long student teaching practicum in a middle or high school science classroom. During this semester, we observed each participant teach at least six lessons. We also collected all of their lesson plans and written reflections from the entire semester. Following the student teaching experience, we interviewed each participant regarding their nature of science understanding and instruction. The goals of this interview were to validate and elaborate upon participants' VNOS-B questionnaire responses, to assess the priority they ascribed to nature of science instruction, and to collect self-report data about nature of science lessons they taught during student teaching. The interviewers made extensive use of follow-up questions to probe in greater depth into participants' thoughts and ideas about the nature of science and if and how they addressed it during their student teaching. To this end, the researchers reviewed with participants their lesson plans addressing the nature of science and asked them to describe specific nature of science lessons. These data sources were analyzed with the goal of describing the full extent of their nature of science instruction and determining the degree to which participants' instruction reflected their informed understanding of the nature of science.

Upon analyzing the data, we found that 13 of the 14 participants explicitly addressed nature of science using a variety of activities and/or explicit discussions while student teaching. The participants who addressed the nature of science typically introduced it in a unit at the beginning of the semester then continued to address specific tenets throughout their student teaching as they fit in the curriculum.

Table 11.5 Preservice teachers' conceptions of nature of science following instruction

Nature of science tenet	Alternative	Transitional	Informed
Scientific knowledge is			
Empirical	0	0	14
Tentative	0	0	14
Creative	0	3	11
Subjective, theory-laden	0	4	10
Roles of observation, inference	0	0	14
Relationship between theories and laws	0	1	13
Social and cultural influences	0	3	9
No single scientific method	0	2	12

Generally, lessons during this initial unit dealt with the empirical nature of scientific knowledge and introducing and distinguishing the process skills of observation and inference. A majority of the participants included explicit instruction on the way scientists use observation and inference to construct scientific knowledge and on the fact that the inferential nature of scientific knowledge is a critical component of its tentativeness. In teaching these nature of science lessons, the participants used a combination of activities from the science methods course and activities they developed on their own. Further, they addressed the majority of the nature of science tenets to which they had been introduced in their science methods course, excluding the tenet that science is socially and culturally embedded.

We found that the majority of participants incorporated the same process skills-based nature of science lessons they learned in the science teaching methods course. For example, to address several target aspects of the nature of science, two participants used the fossil footprints activity that was modeled in the science teaching methods course. These participants presented their students with a progression of images representing fossilized dinosaur footprints (Olsen & Loucks-Horsley, 2000). As each of the images was presented in sequence, they asked students to make observations and inferences about what they saw and to specifically delineate between the two types of knowledge. In the class discussion following the activity, one participant helped students recognize that their initial inferences changed as additional data were collected. The second participant using this activity also included the role of subjectivity in science in the lesson debrief by having her students reflect on their classmates' different inferences and explanations despite all viewing the same data. In another example of participants incorporating process skills activities modeled in the methods course to teach tenets of the nature of science, four participants used the Mystery Tube activity, which required students to observe the anomalous behavior of "black box" apparatus and then infer multiple explanations for its hidden mechanisms. Following this process skills portion of the lesson, participants led a discussion in which the activities were explicitly connected to the relevant aspects of the nature of science, such as the role of observation and inference, and the tentative, subjective, and creative nature of science. Another participant made use of a different black-box activity introduced in the science methods class known as "Mystery Cans" (Bell, 2008). In this activity, two metal cans are connected by a series of tubes, to set up an apparent perpetual flow of liquid between the cans. As in the Mystery Tube activity, the participant challenged students to make and distinguish between observations and inferences, and to develop a model of how the cans worked. In the discussion following the activity, students addressed the possibility of more than one model or explanation fitting the available data, the tentative nature of scientific knowledge, the observational nature of laws, and the inferential nature of theories. In all of these cases, the participants engaged their students in activities that taught students process skills and followed this up with an explicit debrief in which the process skills were linked with the corresponding nature of science tenets.

Not only did the participants translate the activities they learned in the science methods class for use in their own science instruction, but many also found or developed novel lessons to teach both nature of science and science content through process skills-based activities. For example, 12 of the preservice teachers had their students make observations and inferences about a variety of apparently similar objects, including real and wax apples, fake and real rocks, and living versus nonliving things. The primary purpose of each of these activities was to illustrate the importance of distinguishing between observations and inferences and to realize that misleading observations can result in incorrect assumptions. The concluding discussion following each of these activities explicitly addressed multiple nature of science ideas by connecting what students did during the observation/inference activity to how scientific knowledge is developed. Thus, students discussed the inferential nature of theories, the observational nature of laws, and creativity in science. They also discussed how inferences and observations are used to develop the theories and laws that are put forth in science. In another example, a participant developed a lesson that used a mock crime scene investigation to show how events can be inferred from evidence even if there is no witness. The goal was for students to connect the use of indirect evidence in crime investigations to the use of indirect evidence in science. Other aspects of the nature of science discussed while debriefing this activity included the creativity scientists must use when developing hypotheses and the subjectivity of science due, at least in part, to the effect of a researcher's prior knowledge on his or her observations and inferences.

These innovative lessons suggest that the preservice teachers were able to apply their informed conceptions of the nature of science and the process skills-based approach to create and teach new nature of science lessons. But, would preservice teachers who learned accurate conceptions of the nature of science through the process skills-based approach and explicitly taught the nature of science during their student teaching continue their effective nature of science instruction once they had their own classroom?

To determine whether these new science teachers would continue teaching the nature of science, we followed 10 of the 14 preservice teachers in the previous study through their induction year. The purpose of this study was to find out if these 3 male and 7 female teachers would continue to teach the nature of science during their first year of teaching and, if so, whether they used the same approaches and activities employed during their student teaching. The four teachers who did not participate had chosen to temporarily postpone entering the teaching field due to internships, travel, etc. We interviewed the participants both at the midpoint (December) and end (May) of their induction year with the goal of characterizing their nature of science instruction during their induction year. Interview questions addressed how the nature of science fit into the participant's vision of good science teaching, whether they believed their students learned the nature of science from this instruction, how they assessed students' understanding of the nature of science post-instruction, and whether they planned to include nature of science instruction in the future.

We found that the majority of the participants continued to believe the nature of science was an important component to address in their secondary science curriculum because it provides a framework to help students understand the scientific endeavor and the dynamic nature of scientific knowledge. Additionally, these first-year teachers planned and taught many nature of science lessons during their induction-year teaching, some of which were modeled during the science teaching methods course and others that they created themselves. All of the participants used activities that focused on the process skills of observation and inference, emphasizing the roles of these process skills in the development of scientific knowledge as a framework to address more abstract nature of science tenets. Most participants also taught their students lessons about the tentative nature of science using process skills-based lessons. As a group, during their first-year teaching, these participants addressed the majority of the nature of science tenets that were introduced during the science teaching methods course sequence 2 years earlier, excluding only theories and laws and the social and cultural embeddedness of science from instruction.

Despite completing the science methods course more than a year prior, most participants integrated process skills-based nature of science lessons that were modeled for them during this course. Two participants incorporated an activity they had encountered in the science methods class to connect inference to predictions. In this "Cube" activity (National Academy of Sciences, 1998), the participants presented students with a specially prepared cube from which students inferred patterns from numbers or names present on the five visible sides of a cube. Students were then challenged to predict the pattern on the sixth side. As was true during their student teaching, these participants ended this observation/inference activity with discussions explicitly addressing the tentative nature of scientific knowledge and the fact that scientific conclusions often include inferential components. Another participant taught a lesson using fossil fragments that was modeled in the science teaching methods course (Bell, 2008). She provided student pairs with a fossil fragment and instructed them to observe carefully and record in a scale drawing as much detail as they could observe. Next, students were instructed to infer the rest of the organism and its environment. As students shared their drawings with the rest of the class, the participant challenged them to consider how they were able to make the leap from observations of a tiny fossil fragment to a reconstruction of the organism in its environment. This led to discussion about observation and inference in the construction of scientific knowledge and the subjective influence that different background knowledge can have on inferences.

Participants also continued to innovate to expand their repertoire of activities for teaching about observation and inference in the construction of scientific knowledge during their first-year teaching. Of the 10 participants, 7 incorporated process skills-based nature of science lessons they developed independent of the science methods course. For example, one teacher described a lesson he had developed using a Calvin and Hobbes comic strip, where students relied on their observations of surrounding frames to predict what might occur in one frame he had omitted from the sequence. During the activity debrief, the teacher linked students' observations to the role of observation and inference in the development of scientific knowledge. Another teacher developed an original activity to illustrate the inferential nature of predictions and the tentative nature of science. She gave groups of 4 students 10 pieces of a 1000-piece puzzle with a random assortment. The students made observations of what they saw on the puzzle pieces. In their groups, they had to infer what they thought the entire puzzle was about, based just on their observations. As a class, the students then discussed their different inferences and combined these to develop an overall inference of the topic of the puzzle. During the discussion, the teacher explicitly linked the tentative nature of scientific knowledge and the fact that scientific conclusions often include inferential components to the activity. Other novel lessons taught students, through discussion following process skills-based activities, that scientific knowledge is subjective, tentative, creative, and empirical, and that scientists do not use a single scientific method.

Conclusion

The nature of science distinguishes science from other disciplines and provides a framework for understanding science content. As such, the nature of science constitutes an essential component of science education. Understanding the nature of science supports the development of scientific literacy (National Research Council, 1996) and general reasoning skills (e.g. Driver et al., 1996). Though many potential benefits are associated with appropriate nature of science views, both science teachers and their students in general do not hold these appropriate views (Duschl, 1990; Lederman, 2007).

Research has shown that explicit instruction is effective in promoting appropriate nature of science views (e.g., Abd-El-Khalick et al., 1998; Hanuscin et al., 2006; Khishfe, 2008; Scharmann et al., 2005; Schwartz et al., 2004) regardless of whether that instruction is embedded in a specific context such as teaching science content, engaging in scientific inquiry, or discussing socioscientific issues (Bell et al., 2011; Khishfe & Lederman, 2006). However, the real challenge is for teachers to incorporate the nature of science into their instruction once they hold appropriate conceptions. One reason teachers who understand the nature of science do not teach it may be that they learned about the nature of science in a context that they perceive as different from how they plan to teach science. The mismatch of contexts makes it difficult for teachers to see how the nature of science fits into their existing instruction.

This implementation barrier can be addressed in part by teaching teachers the nature of science through the process skills-based approach. This approach uses engaging, critical thinking activities to explicitly connect the nature of science to process skills that teachers already plan to teach. These same activities work well with students of all ages; therefore, the manner in which preservice teachers learn about the nature of science is consistent with how they will teach in their own classrooms.

The preliminary results of our research program indicate that the process skills-based approach is effective in developing accurate conceptions of the nature of science among preservice teachers and in enabling them to translate what they learned into their own science instruction. We found that preservice teachers who experienced nature of science instruction through the process skills-based approach showed substantial improvement in their understanding of the nature of science. Additionally, they taught the nature of science during student teaching, often employing the same explicit approach using activities they learned during the science methods course. Further, they continued to explicitly integrate nature of science ideas through process-skills based lessons during their induction year. Thus, the positive outcomes of the three studies presented suggest that the process skills-based approach to nature of science instruction used in the science methods courses not only helped preservice teachers develop accurate conceptions of the nature of science, but also facilitated their teaching of nature of science lessons during their student teaching and induction years.

Our research results match or exceed those associated in which other explicit approaches were employed, supporting the importance of explicitly addressing the nature of science in instruction (e.g. Abd-El-Khalick & Akerson, 2004; Akerson & Donnelly, 2008; Bell, Lederman, & Abd-El-Khalick, 2000; Khishfe, 2008; Khishfe & Abd-El-Khalick, 2002; Scharmann et al., 2005; Schwartz et al., 2004). The positive results of the three investigations presented above provide a degree of confirmation of the effectiveness of the process skills-based instructional approach that served as a treatment. Add this to the preservice teachers' interview responses that the science methods course was the source of their nature of science understanding, and it is reasonable to conclude that the process skills-based approach used in this investigation was a major contributor to the participants' understanding of the nature of science.

Possessing informed understandings of nature of science alone is insufficient for teachers to translate their knowledge of the nature of science into instructional practice (Abd-El-Khalick et al., 1998; Akerson & Abd-El-Khalick, 2003; Lederman, 1992, 1999; Lederman & Zeidler, 1987; Mellado, 1997). Various interventions designed to promote nature of science instruction have not met with the same success as the process skills-based approach described here (Abd-El-Khalick, 2001; Abd-El-Khalick & Akerson, 2004; Abd-El-Khalick et al., 1998; Akerson et al., 2000; Bell et al., 2000; Lederman, Schwartz, Abd-El-Khalick, & Bell, 2001). However, there is growing evidence that the context in which the nature of science is taught may play a significant role in the application of nature of science understandings to new situations. For example, preservice teachers who experienced explicit nature of science instruction embedded within the context of a socioscientific issue demonstrated increased ability to apply their new understanding to decision making (Bell et al., 2011; Matkins & Bell, 2007).

The results of the three investigations of secondary science teachers detailed in this chapter provide further evidence that contextualized nature of science instruction holds the potential to improve transfer of nature of science understanding to instructional practice. By connecting nature of science instruction to process skills that teachers already recognize as essential to science instruction and plan to teach within their own instruction, the process skills-based approach capitalizes on teachers' preexisting motivation to teach process skills that are recognized as essential to science instruction. Because teachers already know how to teach and plan to incorporate scientific process skills into instruction, explicitly linking nature of science instruction to process skills instruction may help teachers envision how the nature of science fits into their own science instruction. Linking abstract concepts like the nature of science to prior knowledge such as the more familiar process skills also seems to help preservice teachers develop and teach new lessons that link process skills and the nature of science. This process skills-based approach therefore holds great potential to go beyond improving nature of science conceptions to facilitating the transfer to teaching the nature of science.

Ultimately, the most important outcome is the extent to which these teachers are able to help their own students develop an accurate understanding of the nature of science. We hope that the process skills-based approach that our preservice teachers and graduates use leads their students to develop a better understanding of science and to develop a framework for scientific literacy. However, the nature of science literature of the past few decades is replete with examples of instructional interventions that have resulted in disappointing outcomes. Therefore, it is important to continue the line of investigations reported here, rather than rest on the laurels of the preliminary positive results. Future investigations will explore the effectiveness of classroom teachers' process skills-based instruction on K-12 students' understandings of the nature of science. If past investigations are an indication of future results, we can expect the resulting picture to be more interesting and more complicated than originally expected!

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Chapter 12
Impact of a Nature of Science and Science Education Course on Teachers' Nature of Science Classroom Practices

Michael P. Clough and Joanne K. Olson

Introduction

Understanding the nature of science (NOS)—what science is and how it works, the epistemological and ontological foundations of science, how scientists function as a social group, and how society impacts and reacts to science (Clough, 2006)—has been a science education goal for well over a century (Lederman, 1992) and is prominent in contemporary science education reform documents (AAAS, 1989, 1993; McComas & Olson, 1998; NRC, 1996). Many arguments have been put forward for accurately teaching and understanding the NOS (Matthews, 1994; McComas, Clough, & Almazroa, 1998; Robinson, 1968). However, despite the overwhelming agreement regarding the importance of accurately and effectively teaching the NOS, much remains to be done in moving the vision to a reality in elementary through postsecondary science education.

That many science teachers possess inaccurate or simplistic views of the NOS (Abd-El-Khalick & Lederman, 2000; Carey & Strauss, 1970; Lederman, 1992; Miller, 1963, Schmidt, 1967) and are generally unaware of the social and cultural construction of scientific thought (Brush, 1989) is well established. Over 40 years ago Elkana (1970) stated that science teachers' views concerning the NOS trailed contemporary philosophical views by more than two decades. Two decades ago, DeBoer (1991) reviewed the history of science education and noted that an outdated view of the philosophy of science continued to impact classroom practice and permeate popular science curriculum materials—a situation that persists today. Science textbooks, common cookbook laboratory activities, and most audiovisual materials ignore or downplay human influences in research, sanitize the work that eventually resulted in accepted scientific knowledge, and portray science as a rhetoric of conclusions (Cawthron & Rowell, 1978; Clough, 2011; Jacoby & Spargo, 1989; Leite, 2002; Munby, 1976; Duschl, 1990; Rudge, 2000).

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Given the state of science teachers' understanding of the NOS, not surprisingly, studies also document students' and the general public's misconceptions regarding scientists, how science works, and the nature of scientific knowledge (Clough, 1995; Durant, Evans, & Thomas, 1989; Millar & Wynne, 1988; Miller, 1983, 1987; NAEP, 1989; National Science Board, 2002; Rowell & Cawthron, 1982; Rubba, Horner, & Smith, 1981; Ryan & Aikenhead, 1992; Ziman, 1991). The NOS misconceptions held by science teachers, their students, and the general public and promoted in science textbooks coalesce to form a powerful self-supporting network that continues the vicious cycle generation after generation.

These significant misunderstandings regarding the NOS interfere in deeply understanding science content and they impact students' attitudes toward science and science classes. The following student's frustration illustrates how misunderstanding regarding the NOS may affect interest in and understanding of science content.

> What is this game that scientists play? They tell me that if I give something a push it will just keep on going forever or until something pushes it back to me. Anybody can see that isn't true. If you don't keep pushing, things stop. Then they say it would be true if the world were without friction, but it isn't, and if there weren't any friction how could I push it in the first place? It seems like they just change the rules all the time. (Rowe & Holland, 1990, p. 87)

Moreover, Tobias (1990) interviewed a number of successful postsecondary science students and reported that they became disenchanted with science classes and chose different majors, in part, because science courses ignored the historical, philosophical, and sociological foundations of science. Students appear to value learning about the NOS when it is taught in a developmentally appropriate and engaging manner (Meyling, 1997), and Clough, Herman, and Smith (2010) report that postsecondary students' interest in science and science careers increased after having read several historical short stories addressing how scientific knowledge was developed and came to be accepted.

Nevertheless, despite a wide variety of efforts aimed at encouraging teachers to devote explicit attention to NOS instruction, results have, for the most part, been disappointing. Teachers generally appear unconvinced of the need to emphasize the NOS as a cognitive objective (Abd-El-Khalick, Bell, & Lederman, 1998; Lederman, 1998), and see NOS instruction as detracting from their primary mission of teaching science content. Lakin and Wellington (1994) point out that NOS instruction appears to be contrary to "expectations held of science and science teaching in schools, not only by teachers and pupils but also those perceived as being held by parents and society" (p. 186). Too often science teachers simply do not consider the nature of science an important component of science education (Bell, Lederman, & Abd-El-Khalick, 1997; King, 1991). For instance, Bell et al. (1997) followed several preservice teachers through their student teaching experience to determine how extensively they implemented nature of science instruction. Despite significant attention placed on the nature of science in their preservice program, most of these teachers did not show significant explicit attention to teaching the nature of science, and one participant in the study made the following statement: "I don't plan to teach

Table 12.1 Course objectives

1. Develop and articulate a well-informed and fervent rationale for accurately portraying the nature of science in everyday instruction.
2. Develop a set of developmentally appropriate student actions consistent with an understanding of the nature of science.
3. Describe explicit nature of science content, materials, and activities in decontextualized settings (i.e., the focus is exclusively on the nature of science and is divorced from science content instruction).
4. Describe explicit nature of science content, materials, and activities in contextualized settings (e.g., linking the nature of science with science content using typical activities, videos, reading assignments, and authentic historical or contemporary science anecdotes).
5. Describe teacher behaviors and strategies for explicitly drawing the attention of students to and having them reflect on the nature of science.
6. Accurately assess nature of science teaching (and lack of it) in a science lesson.
7. Modify a 2–4 week lesson plan so that it more accurately, explicitly, and consistently addresses the nature of science both decontextually and contextually.

the nature of science. . . . I don't think it is something that I would spend a great deal of time on."

These challenges call for different and more extensive approaches to promoting accurate and effective NOS instruction among science teachers. To this end, the first author developed and taught a course for preservice and in-service teachers devoted exclusively to accurately and effectively teaching the NOS to secondary school students. The two-credit semester length course was directed at achieving the objectives found in Table 12.1.

Students in the course experienced practical science activities in settings where the focus is exclusively on the nature of science (decontextualized NOS instruction), as well as in settings where the focus is primarily on science content (contextualized NOS instruction). The major theme of the course was that significant attention to the nature of science could be achieved with only minor modifications to existing curricula and the teacher's role while implementing those curricula. Toward those ends, students in the class modified science curriculum materials to accurately portray nature of science concepts in both decontextualized and contextualized ways, and addressed teacher behaviors that explicitly draw the attention of students to the nature of science. See Clough (1997, 2006) for a more thorough description of the kinds of NOS activities and instructional approaches modeled and promoted in the course.

The study reported here followed students who completed the NOS course at a large Midwestern research-extensive university to determine their NOS implementation practices in the secondary science courses they later taught. In addition, we sought to determine the connection between their NOS instructional practices and their performance in the course, their rationale for teaching NOS, and the institutional constraints they face. The research questions were as follows:

1. To what extent do study participants effectively teach the nature of science in ways consistent with those promoted in the NOS course?

2. How do study participants' NOS implementation compare to their
    (a) understanding of the nature of science at the completion of the course?
    (b) rationale for teaching the nature of science?
    (c) institutional constraints?

Methodology

Course Context and Participants

All study participants took the NOS course as an elective during the summer prior to the study and at that time were either completing their initial teaching license, a masters degree in science education, or were completing university credits for further professional development and state teaching license renewal. All course participants had previously completed two two-credit courses that addressed the history and nature of science content, and all were pursuing or held secondary science teaching licenses. Both of those prior courses focused exclusively on issues in the history, philosophy, and sociology of science and their relevance to science education, but with no emphasis on pedagogical practices to effectively convey the history and nature of science to students. The first author who created the elective NOS course described above did not teach the two prior courses but was intimately familiar with them, had previously completed more than 20 credits of course work in the history, philosophy, and nature of science during his science education doctoral program, and had 6 years of postdoctoral experience effectively teaching the NOS to high school students prior to designing the course.

Study Procedures and Instrumentation

During the first class session, course participants ($n = 13$) completed informed consent forms agreeing to participate in the study. Immediately afterward, each participant completed 27 VOSTS items (Aikenhead, Ryan, & Fleming, 1989; Aikenhead & Ryan, 1992) that assessed their NOS understanding, and a writing task that asked what they thought were reasons for accurately and effectively teaching the NOS (Table 12.2). At the end of the course, participants submitted a 10–20-day unit plan that they had revised to incorporate both decontextualized and contextualized NOS instruction. Course participants then once again completed the VOSTS and the writing task.

While all 13 course participants agreed to take part in this portion of the study, school district approval to observe classrooms was denied for four teachers; a fifth participant chose to work in a science laboratory; a sixth participant taught in an inaccessible location; and a seventh participant experienced significant difficulty during the semester unrelated to the study and chose to leave the study. Information regarding the remaining six teachers that made up this study appears in Table 12.3.

Table 12.2 Writing task for determining study participants’ reasons for teaching the NOS

A friendly and interested colleague asks you to write a letter explaining why accurately teaching about the nature of science instruction is important for teachers and students. Below please write the reasons you would provide so that colleagues, administrators, and parents would understand your rationale.

Table 12.3 Study participant information

Participant	Gender	Years teaching	School type
1	M	5	Large suburban
2	F	1	Small rural
3	F	1	Small rural
4	M	1	Small rural
5	M	3	Large urban
6	M	6	Large suburban

During the fall semester after having completed the NOS course, the six study participants were observed teaching on three separate occasions. Each visit was arranged with the teacher in advance. During those visits we examined classroom artifacts (bulletin boards, student work, handouts, and lesson plans), and observed classroom interactions. During these classroom observations we looked for evidence of the following:

1. Interaction between the teacher and students that explicitly addressed NOS ideas, questions teachers asked to draw students’ attention to NOS ideas, and student questions about the NOS;
2. Teachers’ accurate use of or avoidance of language having NOS implications (e.g., law, theory, prove, truth, how does a particular idea *account* for data rather than the data *tells*, etc.);
3. Decontextualized NOS activities and discussions;
4. Contextualized NOS activities and discussions;
5. Classroom artifacts that sent messages about the NOS.

These practices reflect the objectives of the NOS course that study participants had completed during the previous summer and the central ideas that a prior analysis (Olson & Clough, 2003) had established were clearly emphasized during that course. Field notes were taken by each researcher and compared after the visit.

Teachers’ implementation practices on the above criteria were coded low, medium, or high. Low ratings were given when teachers classroom practices and artifacts indicated they implemented decontextualized NOS instruction and had their students reflect on those experiences, but did not create or capitalize on clear opportunities to address the NOS with their students in the context of science content being taught or inquiry activities being conducted. Low implementers might also be observed stating incomplete or somewhat inaccurate NOS ideas at times, and they did not engage students in reflecting on NOS ideas that were present in more contextualized situations.

The medium NOS implementation category was used for teachers who implemented decontextualized NOS instruction and had their students reflect on those experiences, but who also created and capitalized on at least some clear opportunities to address the NOS with their students in the context of science content being taught or inquiry activities students were conducting. However, medium implementers are noticeably less effective than high implementers at drawing their students' attention to and helping them grasp desired NOS ideas.

Teachers in the high implementation category not only employed decontextualized NOS activities and had their students reflect on those experiences, but also often created and capitalized on opportunities to address the NOS with their students in the context of science content being taught or inquiry activities being conducted. Their NOS instruction was explicit, reflective, and ubiquitous in many of their science instruction contexts. These teachers were effective at drawing their students' attention to key NOS ideas in multiple contexts and having them reflect on those NOS ideas.

Following each visit, we conducted semi-structured interviews with each teacher to ascertain (1) their goals and objectives for the lesson; (2) their impression of the lesson; (3) what NOS ideas they have previously taught to their students; (4) how they have conveyed those ideas to their students, and (5) successes and challenges they encounter in their attempts to teach the NOS. After comparing field notes from the all three observations and interviews, the two researchers jointly developed a profile of each teacher. Table 12.4 provides an example of such a profile. These profiles along with more detailed observation notes and artifact analysis were used to determine the NOS implementation patterns of study participants and assign them an overall low, medium, or high implementation category. For instance, Teacher 3's NOS implementation was coded as low. She taught a decontextualized NOS unit at the beginning of the school year and subsequently did not explicitly incorporate NOS instruction in the context of science content or activities, nor did she ask questions or make other instructional moves that would have drawn students' attention to NOS ideas and have students reflect upon them.

The teachers' VOSTS and writing task were analyzed separately by both researchers. We looked for changes in responses on the VOSTS items before and after the course, as well as after a year of teaching. Areas where changes occurred were noted and these shifts were compared to implementation practices and student responses on the questionnaire. The writing task was analyzed to determine how study participants' rationale for teaching the NOS changed with classroom experience and if high implementers had different rationales than low implementers. A coding system developed by Bruxvoort, Olson, Clough, and Vanderlinden (2003) using both open and axial coding was used to generate and then reduce study participants' writing task responses to the categories appearing in Table 12.5.

In late November/early December, students in the six teachers' classes completed a brief voluntary and anonymous questionnaire to determine the kind and frequency

Table 12.4 Sample teacher profile

Teacher 3 teaches tenth grade biology. She says teaching the NOS is very important and she claims to have emphasized it a great deal in her classroom. During our visit, students were very unruly and disrespectful of one another and of the teacher. Class time was spent entirely on issues of science content, with a great deal of student seatwork using their textbooks. Teacher 3 appeared frustrated and had difficulties getting the students on task.

Several opportunities to address the nature of science were missed during the lesson. The portion of the book they were reading contained inaccurate historical examples. Students and the teacher frequently misused the term *theory* and *prove*.

After the lesson, Teacher 3 expressed her frustration with the students and the administration. She said she had students complete some VOSTS items at the beginning of the year, and had done some decontextualized activities such as the tricky tracks and mystery tube activities, but "I haven't had time to address the nature of science since then." When asked why, she said she felt pressure to cover content and her frustration with the students' behavior prevented her from having the desire to expend extra time and effort to include the NOS when they couldn't even handle science content. She also cited coaching responsibilities and family issues as preventing her from spending extra time to prepare for classes. When asked about the administration, she said they do not understand or value the NOS and want the class to cover the science content in the textbook.

Table 12.5 Rationale for teaching the NOS provided by study participants

1. Increases student interest in science content
2. Increases student interest in science careers/courses
3. Increases student appreciation of science
4. Increases understanding of science content/understanding of what is fundamental content
5. Teachers teach NOS regardless of intention, so we may as well do it right
6. Understand science and its relationships to technology and society (e.g., funding)
7. Develop more informed citizens (voters, jurors)
8. Students will understand that science is a human enterprise
9. Students will better understand science processes/how science is done (doing science requires creativity, no algorithmic scientific method exists, etc.)
10. Shows connection between subjects (history, etc.)
11. Understand the difference between science, pseudo-science, and religion
12. I have to; it's in the reform documents (standards, etc.)
13. Students will find science relevant

of NOS instruction they perceived was addressed during the fall semester. We also asked students to briefly write about their impressions of NOS instruction.

At the end of the school year, a structured interview was conducted with the teachers to determine their perceptions regarding (1) the extent to which they had implemented NOS instruction; (2) what helped or hindered their teaching of the NOS; (3) confidence in their understanding of the NOS content and pedagogy; (4) their goals for students, including their rationale for teaching the NOS; (5) their future plans for NOS instruction; and (6) their feedback regarding the course and what could have been done to better prepare them to teach the NOS. To increase the likelihood that teachers would honestly critique the NOS course and describe their own NOS teaching experiences, all year-ending interviews were conducted and analyzed by the second author, who did not teach the NOS course.

The interviews were conducted by telephone, audiorecorded, and transcribed. Analysis was conducted using Strauss and Corbin's (1998) open and axial coding techniques to elicit patterns of implementation and common themes. Teachers completed the 27 VOSTS items and the writing task one final time.

Findings

Extent and Character of Teachers' NOS Implementation

All six study participants made deliberate efforts to teach the NOS, although they ranged widely in their implementation practices. Four of the six taught the NOS consistently and contextually, both in decontextualized settings and contextualized within science content instruction and inquiry activities. They often asked questions that had students reflect on particular NOS issues relevant in everyday science instruction. Of the remaining two teachers, one often addressed the NOS in a decontextualized manner at the beginning of class, and the other taught a NOS unit in a decontextualized manner at the beginning of the school year. Neither of these two low NOS implementers appeared to purposely teach the NOS outside these very limited contexts. Table 12.6 summarizes each study participant's overall NOS instructional implementation rating.

The four teachers categorized at high levels of implementation had much in common. First, they all taught the nature of science both decontextually (the focus of a NOS lesson or activity was unrelated to science content instruction), as well as contextually (NOS instruction was embedded within science content in a lesson and at times included examination of scientists' work and statements about their work). One of the four high-implementation teachers (Teacher 2) relied solely on activities used during the summer NOS class, but the other three used the class activities and supplemented their units with additional resources they found on their own. All four high implementers used a variety of NOS instructional strategies that included decontextualized puzzle-solving activities (e.g., tube activities, gestalt switches, etc.,), additional readings outside the textbook (such as excerpts

Table 12.6 Participants' NOS implementation levels

Teacher	NOS Implementation
1	High
2	High
3	Low
4	Low
5	High
6	High

from James Watson's "The Double Helix") that provided rich material for addressing important NOS issues, videos such as "Lorenzo's Oil" that were also used to raise NOS issues, explicit class discussions about a number of NOS issues (e.g., to what extent was the structure of DNA created and/or discovered), required student journal writing addressing NOS issues, and assessments that included questions addressing the NOS. These teachers created, recognized, and utilized opportunities within everyday lessons to explicitly raise NOS issues with their students.

The two teachers at low levels of implementation missed significant opportunities to address the NOS. Teacher 4 identified opportunities during a lesson where he could have addressed a NOS idea, but he deliberately chose not to do so, stating that he felt the students had already had a lot of NOS and needed more time and focus on science content. Thus, while this teacher asserted in his written response to the question appearing in Table 12.2 that NOS and science content are equally important, he gave priority to "covering" the biology content and made pedagogical decisions that detracted from accurate and effective NOS instruction. When asked what biology content took such high priority for his students, he referred to content that was included in his own high school biology class. Teacher 4's decision to downplay NOS instruction in favor of covering science content was made even though no mandated curriculum or high-stakes science content exam constrained his decision making. His solution to the problem of teaching the NOS while still "covering" the content was to occasionally set aside approximately 5 min in a class to address a NOS concept via a decontextualized NOS activity. Ironically, teacher 4 did not appear to consider that periodically integrating the NOS in a contextualized fashion would require little or no more time than the decontextualized NOS instruction he was implementing.

Teacher 3 taught a decontextualized NOS unit at the beginning of the school year and did not plan for and incorporate accurate and effective NOS instruction beyond that early effort. Even when opportunities clearly existed to address the NOS in the normal course of teaching science content, this teacher chose not to do so. While expressing a desire to incorporate NOS while teaching content, this teacher was most concerned with classroom management issues and related pressure from the principal which weighed heavily on the teacher's instructional decision making and practices. Our impression was that this teacher was trying to survive the year rather than concentrate on ways to improve NOS practice.

Our overall assessment of teachers' NOS instructional practices matched students' perceptions of NOS instruction occurring in their class. Students in all four teachers' classrooms who administered the student questionnaire (Teachers 2, 4, 5, and 6) wrote responses indicating that their teacher devoted at least some time to teaching the NOS. The first question asked of students was "What kinds of activities or discussions occurred in class that help you understand what science is like and how it works?" Student responses were coded *positive* if they could generate a specific NOS-related course experience. A *neutral* code was assigned if the student made a neutral comment about the course but whether the student was referring to NOS instruction could not be determined. A *negative* code was assigned if students made a negative statement about the course but whether the student was referring

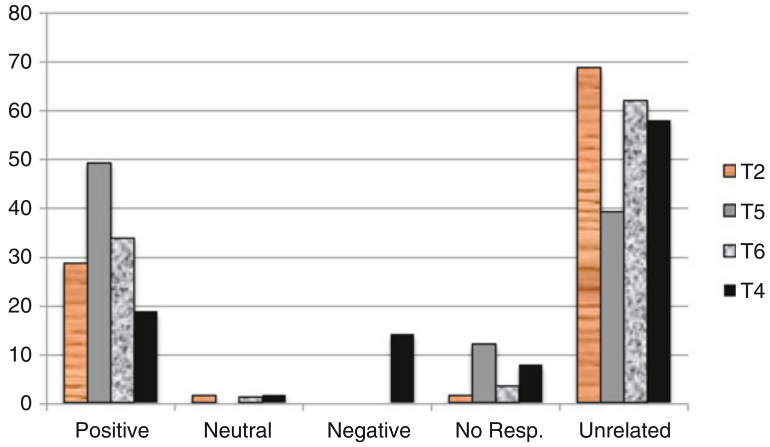

Fig. 12.1 Percentage of student responses that recalled NOS activities or discussions

to NOS instruction could not be determined. A code of *unrelated* was assigned to any response that provided course experiences, but the experience appeared to be designed to teach science content and not the NOS. Many students interpreted the question to mean "What activities helped you learn science content?" and thus provided a list of laboratory experiences that were coded "unrelated." Figure 12.1 provides the percentage of students in each response category for each of the four teachers whose students completed the questionnaire. Students' responses in high NOS implementation teachers' classrooms (Teachers 2, 5, and 6) are represented by the three bars at the left in each category. Students' responses in the low NOS implementation teacher's classroom (Teacher 4) appear to the far right in each category (represented by the dark bars).

Responses appearing under the *positive* category identified specific nature of science concepts their teachers taught (such as the differences between basic and applied science, the lack of a single scientific method, how a scientist's prior knowledge affects observations, etc.,).

At least 18% of the students in all four teachers' classes could identify that they were learning the nature of science, reflecting that even the low-implementation teacher addressed the NOS to some extent. Notable is that the high-implementation teachers had a much greater percentage of students who could recall specific instances in which the nature of science was addressed. The following quotations from students illustrate the kinds of activities in which students were engaged:

> We looked at a lot of pictures where you could see two things in one object such as an old woman or a young lady. Showing us pictures like that showed us how our prior knowledge can affect which one we saw. We did many of those to help us. We filled out a sheet and it had different experiments and basic/applied science on it. We had to number least to greatest on what we would give money to. And we said what percent we would give them. That showed us how basic stuff can turn into applied science and so on. (Teacher 5, student response 1.54)

> We had a lot of discussions on the nature of science and almost every experiment he pointed out that our observations might be based on our prior knowledge. (Teacher 5, student response 1.72)
>
> We had a lot of discussions about how there are no facts in science, only best answers. I didn't know that before. We also had many discussions on different points of view of different scientists. We had lots of discussions on the similarities and differences, also interactions between applied science, basic science, technology, and how prior knowledge affected them. (Teacher 2, student response 2.01)
>
> We did charts and a lot of discussions about prior knowledge and about how science cannot be proved. (Teacher 2, student response 2.16)
>
> One of the big things that I did was a science fair project. It showed me an idea of how scientists conduct research. I know they have to go through lots of research and work and it's not just a single method. (Teacher 6, student response 1.19)

The consistency between students' reports of NOS instruction, teachers' self-reporting, lesson planning artifacts, and our classroom observation together provide compelling support for our categorization of teachers' NOS instructional implementation practices. For example, one teacher claimed he did not spend time on the difference between basic and applied science, and students' responses on the questionnaires, our classroom observations, and our analysis of lesson planning artifacts support this.

Student Perceptions of Their NOS Learning

As part of the questionnaire, students were asked to describe how their views about science and science classes have changed since the beginning of the school year. Responses were coded *positive* if students reported positive changes in their understanding of science or science classes, *neutral* if they made a statement that was related to the question but was neither positive or negative, and *negative* if they responded negatively about science or science classes. *Unrelated* was used when students responded in a way that was unrelated to the question. The percentage of students who responded in each category is provided in Fig. 12.2.

Figure 12.2 illustrates the differences between teachers who implemented NOS at high and low levels. Teacher 4 (in the dark bar on the far right for each category) is a low-implementation teacher. Despite 18% of his students identifying that they were learning NOS concepts in question 1, their overall response to the course was neutral or negative, with most students making comments about unrelated topics and only 8% perceiving positive changes in their views about science and science classes. One student remarked, "They have not changed at all, at the beginning I was going to just get my credits for science and quit and I am still going to do that because our science program needs help" (Teacher 4, student response 1.58). Another said, "Yes, I dislike it a lot more" (Teacher 4, student response 1.59).

The perceptions of students in classes where the NOS was taught at a high level of implementation differed dramatically. Between 65 and 92% of the students in those classes reported positive changes in their views toward science and science classes. One student wrote, "At the beginning of the term I came from prior classes

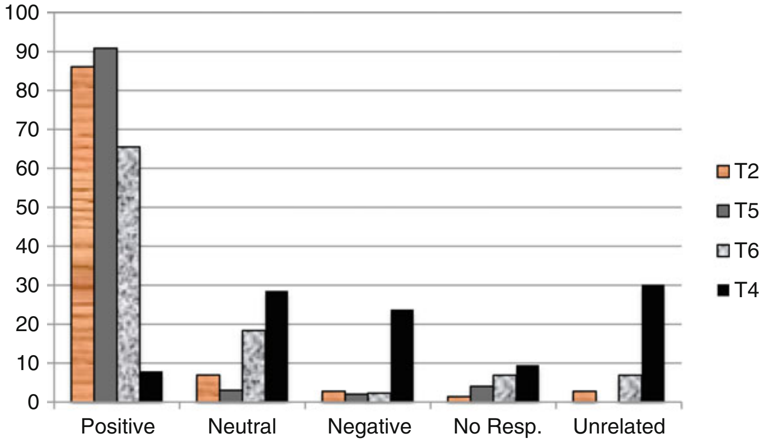

Fig. 12.2 Percentage of student responses about how their views of science and science classes have changed

that only taught us about the scientific method and how it is used for everything in science. Now coming from [Teacher 5] I know that is not true. And never once in any of my other classes had we ever talked about the nature of science. Some things I never even had a view on, now I do." (Teacher 5, student response 1.20)

Students, particularly those in the high NOS implementation classrooms, reported that they enjoyed learning NOS concepts and that it changed their views of science. Classroom observations support this finding, as we viewed several classes where students were engaged in extensive and at times sophisticated discussions regarding NOS ideas. Students also told us they had previously disliked science, but enjoyed learning about the limitations of science and the "human side" of the scientific enterprise. For example, in response to the question "How have your views about science and science classes changed since the beginning of this school year?", students from one of Teacher 5's classes, a high NOS implementation teacher, wrote

> I learned that scientists use their prior knowledge to solve problems. (Teacher 5, student response 1.07)
>
> Now I'm skeptical about most of the stuff we learn. (Teacher 5, student response 1.15)
>
> I used to think there was a method to science, but now I realized that very few people use the scientific method. I also learned that a lot of scientific things are discovered too. (Teacher 5, student response 1.18)
>
> I had always been taught to the book, and "it was always right." My previous teachers never explained how unexact (sic) of an art science can be (and is.). We explored the fact that what is in our books may not always be correct, it is just the most accepted answer. I no longer trust my book, etc., to be the absolute, end all, answer to my science-related questions. Learning about the nature of science has also helped me to look deeper into how scientists operate and how many discoveries came to be (biased and not exact, etc.). I would say that this class has opened my eyes to the way I perceive science to truly be, not this exact study of things and nature that yeild (sic) perfect answers, because in reality science is far from that! But still, it's the best we have. (Teacher 5, student response 1.19)

> At the beginning of the year I thought that scientists were just guys in white lab coats. Now I understand. (Teacher 5, student response 1.24)
>
> Now I know how scientists come up with answers. (Teacher 5, student response 1.26)
>
> I didn't really have any views to begin with, so I can't really say that they changed. (Teacher 5, student response 1.30)
>
> I was taught in previous years that there was a specific way to do science. By following the scientific method. In this class I have learned that there really isn't a scientific method. I know now a better definition of what science is. (Teacher 5, student response 1.38)
>
> I know now that there is more to science than most people think. (Teacher 5, student response 1.39)
>
> I didn't used to like science very well but after having [Teacher 5] for a term my ideas have changed. I still don't want to have science as my career but as far as taking science when I am in college I would really enjoy that. (Teacher 5, student response 1.63)
>
> I viewed science as a bunch of smart people doing high tech big funded research that is really important. But now I view basic research with application as a necessity in order to have applied science anyway. (Teacher 5, student response 1.81)

We have included students' statements from a single class of teacher 5 rather than across classes and teachers to illustrate how pervasive such comments were in the high NOS implementation teachers' classrooms. The specificity and depth of NOS ideas to which students refer is not limited to a few high-achieving students. The number of positive student responses was typical of high-implementation teachers' classes, regardless of the teachers' years of experience or school setting.

Teachers' NOS Understanding and Relation to Instructional Practices

All six study participants expressed a robust understanding of the NOS on the summer NOS course pre- and post-VOSTS assessments and again at the end of the fall semester in which this study took place. Rather than select one of the empirically derived multiple-choice responses, study participants often selected "None of the above choices fits my basic viewpoint" and proceeded to write a response illustrating sensitivity to subtleties with language and ideas related to the NOS. Recall that all six study participants had previously completed two required NOS content courses and elected to complete the NOS pedagogy course. Thus, their excellent understanding of the NOS is unsurprising.

In addition to having a robust understanding of the NOS, all six teachers performed very well on course assignments that required them to apply that understanding to effectively teaching the NOS to secondary school students. All six teachers performed admirably at modifying a 10–20-day science lesson of their choosing so that it more accurately, explicitly, and consistently addresses the nature of science both decontextually and contextually. Teachers used puzzle-solving activities, Gestalt switches, outside materials that addressed the NOS or created opportunities to accurately address the NOS, excerpts from primary source material, class discussions, and assessments that promoted NOS as a cognitive objective.

Interview dialogue also supported participants' understanding of both NOS content and pedagogy. Thus, study participants' understanding of the NOS and how to effectively incorporate NOS instruction in lesson plans was insufficient to explain differences in their NOS teaching practices.

Teachers' Rationales for Teaching the NOS

The raw number and type of rationales provided by teachers prior to the summer course was the same for teachers who later were categorized as low and high NOS implementers. Among teachers who implemented NOS at high levels, the raw number of rationales they provided for teaching the NOS increased from the beginning to the end of the course and increased again at the end of the fall semester of teaching. When examining the categories appearing in Table 12.5, the number of times rationale 4 appeared (NOS helps students understand science content) differed between high and low implementation teachers. None of the teachers provided this rationale prior to the summer course. At the end of the summer course, this rationale was present in all four high implementation teachers' writing task, and was vaguely present in one low-implementation teacher's writing task, although it was combined with "inquiry" and could refer to process skills. At the end of the fall semester, after teaching the NOS to students, three high-implementation teachers cited learning of science content as a rationale to teach NOS. Low NOS implementation teachers did not provide this rationale for teaching the NOS and instead tended instead to focus on more general rationales related to teaching such as "I have to teach it anyway because it is in the standards," "NOS is taught no matter what, so I should teach it accurately," and "NOS improves teaching."

While teachers categorized as low implementers conveyed a robust understanding of NOS content and effective NOS pedagogy, no noticeable changes in their rationales for teaching NOS occurred. The number of coded responses remained stable; in other words, they did not increase or decrease the number of reasons that NOS should be taught. Unlike the high implementers, rationale 4 did not increase over time. Like the high implementers, rationale 4 was missing prior to the course, but unlike the high implementers, this rationale did not appear in their later writing tasks.

Institutional Constraints and Implementation Level

All six teachers in our study cited institutional constraints as hindering their efforts to effectively teach the NOS. This is consistent with the findings of Bell et al. (1997) who found that issues of time and content coverage impeded NOS instruction implementation. Despite these stated concerns, however, this study raises questions about the sufficiency of these constraints to explain teachers NOS implementation practices.

For instance, both low NOS implementers (teachers 3 and 4) cited their inexperience as affecting the extent of their NOS instruction. Both were first-year teachers and stated that they were uncomfortable with unanticipated student responses, and this caused them to decrease the amount of time spent addressing NOS issues. But this reason is suspect because unanticipated student responses also occurred when they both taught science content, yet they persisted in teaching those ideas. Moreover, high NOS implementation teacher 2 was in her first year of teaching and also noted her surprise at student responses to her science content and NOS questions, but she persisted in her efforts at effective NOS instruction.

Low NOS implementation teacher 3 cited concerns with the principal over her classroom management as interfering with NOS instruction. Yet teacher 1 had the highest NOS implementation level and faced open resentment from his science department colleagues who were upset that he wasn't doing precisely what they did with their students. This opposition toward teacher 1's extensive NOS instruction then spread to the principal who then voiced that similar teaching and learning experiences should exist in all biology classes at the school. High NOS implementation teacher 5 also faced similar colleague hostility, and high-implementation teacher 6 noted lack of support/indifference to his NOS instruction. Only high-implementation teacher 2 noted significant freedom, but not encouragement, from science colleagues and the school administration to teach the NOS.

Conclusions and Implications

All six teachers taught the NOS and four of the six did so extensively throughout the fall semester in which this study took place. This conclusion is supported by classroom observations, classroom and lesson material artifacts, and students' reported perceptions. All six teachers drew from the NOS activities presented during the summer NOS course, but the four high NOS implementation teachers incorporated both decontextualized and contextualized NOS instruction whereas the two low NOS implementation teachers limited their NOS instruction to isolated decontextualized instruction. These two low NOS implementation teachers neither planned for contextualized NOS learning experiences nor did they capitalize on NOS opportunities that clearly arose while teaching science content.

All six teachers conveyed an excellent grasp of NOS content and effective NOS pedagogy. All six reported institutional constraints that worked against effective NOS instruction. Both low-implementation teachers noted a lack of support for their efforts to accurately teach the NOS, and reported that other instructional concerns were more pressing to their administrators and colleagues. However, the most severe constraints and even some open hostility toward NOS instruction were faced by teachers 1 and 5, who were both high NOS implementers. Thus, institutional constraints are an insufficient explanation for the level of NOS instruction incorporated by teachers in our study. This does not mean that institutional constraints are unimportant in whether a teacher does or does not place significant attention on

NOS instruction, but obviously the four high-implementation teachers in our study did not permit those institutional constraints to interfere in teaching the NOS.

So the question arises: what about the high NOS implementers might account for their perseverance at teaching the NOS despite the institutional constraints they faced? What *was* clearly different between the high and low NOS implementation teachers in our study is that all four high NOS implementers possessed clear and fervent rationales for teaching the NOS that appeared to compel them to address the NOS in all aspects of their teaching despite the constraints they faced. Interestingly, all four high NOS implementation teachers asserted that NOS instruction helps students learn science content as one of their rationales for why the NOS should be accurately and effectively taught. What these four teachers saw as the precise connection between the NOS and understanding science content was not clear in their writing, but the summer NOS course emphasized the following connections (Clough, 2004):

- Understanding the NOS helps students understand and work from the assumptions that underlie scientific knowledge;
- Understanding the NOS can raise students' interest in science and science classes, thus improving motivation to learn the science content;
- Teaching the NOS improves a science teacher's science content instruction (e.g., explicitly addressing the NOS will make clear the construction and reconstruction of science ideas, and will help students understand that some of the ideas they hold were once held by scientists. This will make clear to both teachers and students the conceptual journey that students must make in understanding contemporary science ideas.).

The four high-implementation teachers' comments and classroom practice were consistent with a view that science content teaching and learning would be improved with NOS instruction seamlessly incorporated throughout science instruction. The two low NOS implementation teachers did not express the same tight link between science content and NOS content, and gave priority to the former.

As noted earlier in this chapter, Lakin and Wellington (1994) wrote that NOS instruction appears to be contrary to "expectations held of science and science teaching in schools, not only by teachers and pupils but also those perceived as being held by parents and society" (p. 186). However, perhaps a more precise representation of the situation may be that attempts to *accurately* portray the NOS are contrary to the expectations held of science teaching in schools! The NOS misconceptions held by many science teachers, their students, administrators, parents, the general public, and promoted in science textbooks coalesce to form a powerful self-supporting network that draws attention to teachers who attempt to accurately portray the NOS. This unsought attention is unlikely to be met with encouragement, and may draw reproach, particularly if a teacher is struggling in any other aspect of his or her teaching. Perhaps a conviction that NOS instruction is not an "add-on" distraction, but rather an integral part of effective content instruction is crucial for teachers to incorporate NOS instruction at high levels despite institutional constraints.

All six teachers in our study stated that they are committed to teaching the NOS, and all did so in some form. But the four high-implementation teachers expressed a more compelling and passionate rationale for teaching the NOS. They were resolute about accurately and effectively teaching the NOS, and were willing (but did not seek) to stand out among their science-teaching colleagues and "buck the system," potentially putting themselves at risk of offending colleagues or having their practices questioned. These high NOS implementation teachers' commitment to accurately and effectively teaching the NOS was also apparent in our classroom observations that made clear they exerted more time and effort preparing to teach the NOS. A passionate rationale for students to accurately understand the NOS, a teacher's willingness to stand out from others regarding teaching practices, and time and effort devoted to teaching appear in our study to be important factors affecting NOS implementation.

While generalizability is limited on a study of six teachers, our study supports the contention that teachers experiencing a NOS course emphasizing the objectives in Table 12.1 will implement the nature of science within secondary science classes, and most at high levels. Teachers in our study cited the value of learning ways to implement NOS instruction within the science content, thus removing the pressure to "add" yet another unit to an already overburdened curriculum. They used activities from the course in their own teaching, and five of the six sought out additional activities, articles, and other resources to incorporate the NOS within the content they taught.

Students are aware they are learning NOS when teachers make the nature of science an explicit part of instruction, and when implemented well, students are very positive about learning NOS concepts. Common responses among students included appreciation for complexity; they enjoyed knowing that multiple methods exist, that scientists can change their minds, that prior knowledge affects what scientists see and the interpretations they make, and that scientific knowledge itself may be open to change. Some student responses conveyed they had questions about NOS issues prior to the course that were finally answered when they studied NOS. For example,

> I never gave much thought to "prior knowledge altering one's perception" but before [teacher 5's] class I would often get into heated debates with my previous science teacher over "the scientific method." I always thought that there isn't just one scientific method and [teacher 5] has now shown me I was right. (Teacher 5, student response 1.58).
>
> I think I was very narrow minded about a lot of things and don't think I really applied myself to try and change my views (mainly because my eighth grade science teacher). Being in this class helped me see that there is more than one way to do almost everything and that most times scientists' ideas are altered because of their other thoughts and feelings. [Teacher 5] explained in detail many things I had questions about. (Teacher 5, student response 1.54).

Thus, while many science teachers view NOS instruction as an "add-on," students in our study expressed appreciation that they are finally learning how science really works, and appear to value NOS instruction. No student in any class of the high-implementation teachers stated that they felt it was a distraction to what they "should be learning," despite this being a common concern among many science teachers.

This study will be continued as additional teachers complete the course. We intend to develop patterns of implementation and to determine what factors most inhibit successful NOS instruction. In the mean time, we have determined that courses designed to promote NOS teaching must address the misconception that the nature of science is an "extra" to be added on to the curriculum. Instead, teachers need both practical strategies to implement NOS instruction within the context of the content they are teaching, and support in developing the view that NOS instruction will help students learn science content. In addition, they need to correctly and consistently identify where in their units they can include NOS concepts and take advantage of those opportunities.

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