Chapter 28
Nature of Science in the Science Curriculum: Origin, Development, Implications and Shifting Emphases

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28.1 Introduction

Before proceeding to the substance of this chapter, it is important to clarify what I mean by *nature of science* (NOS) and note the ways in which I use the term differently from some others. A number of authors seek to restrict its use to the characteristics of scientific knowledge (i.e. to epistemological considerations) and to exclude consideration of the nature of scientific inquiry.[1] This might strike some as an odd decision, given that much of our scientific knowledge and, therefore, consideration of its status, validity and reliability is intimately bound up with the design, conduct and reporting of scientific investigations. Moreover, teaching activities focused on NOS often include empirical investigations and/or critical scrutiny of existing data. Thus, as Ryder (2009) points out, the conduct of scientific inquiry and epistemological considerations are related conceptually, procedurally and pedagogically. Lederman (2006) has acknowledged that 'the phrase 'nature of science' has caused the confusion and the phrase 'nature of scientific knowledge' might be more accurate. The conflation of NOS and scientific inquiry has plagued research on NOS from the beginning' (p. 2). In other words, it would be less confusing to readers if authors used the term 'nature of scientific knowledge (NOSK)' when referring to strictly and/or solely epistemological matters. In common with

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[1] Abd-El-Khalick (2001, 2004, 2005), Abd-El-Khalick and Akerson (2004, 2009), Abd-El-Khalick et al. (1998, 2008), Bell (2004), Flick and Lederman (2004), Hanuscin et al. (2006), Khishfe and Abd-El-Khalick (2002), Khishfe and Lederman (2006, 2007), Lederman (2006, 2007), Lederman and Abd-El-Khalick (1998), Lederman et al. (2001, 2002).

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several other recent publications,[2] the definition of NOS deployed in this chapter encompasses the characteristics of scientific inquiry; the role and status of the scientific knowledge it generates; the modelling that attends the construction of scientific theories; the social and intellectual circumstances of their development; how scientists work as a social group; the linguistic conventions for reporting, scrutinizing and validating knowledge claims; and the ways in which science impacts and is impacted by the social context in which it is located.

Given this much broader definition of NOS, it is quickly apparent that arguments for including NOS in the science curriculum have a long and chequered history. The long-standing tradition of concern for 'the public understanding of science' in the United Kingdom, encompassing much of what I refer to as NOS, dates back to the early years of the nineteenth century. As Jenkins (1990) notes, science was vigorously promoted through the activities of the numerous Mechanics' Institutes and Literary and Philosophical Societies and further supported by public lectures, scientific demonstrations and 'a remarkable variety of books, journals, tracts, pamphlets and magazines, many of which would be categorized today as 'teach yourself publications" (p. 43). Perhaps the earliest proposal for an NOS-oriented curriculum at the school level was Henry Armstrong's heuristic approach,[3] published in 1898, although it is important to note that Armstrong's interest in NOS was mainly pedagogical and motivational; the real purpose was to acquire and develop scientific knowledge. In contrast, John Dewey (1916) argued that familiarity with scientific method was substantially more important than acquisition of scientific knowledge, particularly for those who do not intend to study science at an advanced level. Similarly, Frederick Westaway (1929), an influential HM Inspector of Schools in the United Kingdom in the 1920s, made a strong case for a curriculum focus on NOS:

> Now that science enters so widely and so intimately into every department of life, especially in all questions relating to health and well-being, it is important that the community should have a general knowledge of its *scope and aims*. (p. 9, emphasis added)

Some years later, similar rhetoric formed the basis of Joseph Schwab's (1962) advocacy of a shift of emphasis for school science education in the United States away from the learning of scientific knowledge (the products of science) towards an understanding of the processes of scientific inquiry and the structure of scientific knowledge – a line of argument that eventually led to a string of innovative curriculum projects (PSSC, BSCS, CHEM Study, CBA, ECSP, etc.). NOS-oriented developments in the United Kingdom during the 1960s included the Nuffield Science Projects (with their emphasis on 'being a scientist for the day' and 'developing a proper attitude to theory') and the Schools Council Integrated Science Project (SCISP). However, as a direct consequence of their reliance on an impractical pedagogy

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[2] Allchin (2011), Bartholomew et al. (2004), Clough (2006, 2011), Clough and Olson (2008), Elby and Hammer (2001), Hodson (2008, 2009, 2011), Kelly (2008), Matthews (2012), Osborne et al. (2003), Rudolph (2000), van Dijk (2011), and Wong and Hodson (2009, 2010).

[3] See Brock (1973), Jenkins (1979), Layton (1973) and van Praagh (1973).

of discovery learning and the naïve inductivist model of science underpinning it, these somewhat elitist courses failed to deliver on their rhetoric and promise. Those of us who were required to adopt the pedagogy of discovery learning during its heyday in the 1960s will vividly recall the frustrations of not being allowed to provide students with any guidance or suggest alternative lines of approach when investigating phenomena and events.[4] Subsequently attention shifted towards the so-called process approaches to science education, exemplified by *Warwick Process Science* (Screen 1986, 1988), *Science in Process* (ILEA 1987) and *Active Science* (Coles et al. 1988), which envisaged scientific inquiry as the application of a generalized, all-purpose algorithmic method. A similar shift occurred in Australia, with the publication of the *Australian Science Education Project* (ASEP 1974), and in the United States, with initiatives such as *Science-A Process Approach* (AAAS 1967) being developed on the basis of Robert Gagné's (1963) claim to have identified thirteen basic skills of scientific inquiry.

After a period of decline, interest in NOS underwent a remarkable revival in the decade and a half between 1977 and 1992, with the publication of a number of opinion pieces and commissioned reports,[5] the establishment of the International History, Philosophy and Science Teaching Group (1987) and the first of the now biennial IHPST conferences in Tallahassee in 1987 – developments that led, through the prodigious efforts of Michael Matthews, to the foundation in 1992 of *Science & Education*, the first journal devoted primarily to NOS issues in education. Of particular significance during this period was the incorporation of NOS as a key component in the National Curriculum for England and Wales, established in 1989 following the Education Reform Act of 1988. Another landmark was the publication of Matthews' book *Science Teaching: The Role of History and Philosophy of Science* (Matthews 1994).

Although there has been continuing controversy about what the NOS component of the curriculum should comprise and how it should be implemented (Donnelly 2001), the overall curricular importance of NOS understanding per se is no longer in dispute. Indeed, it has been subsumed within the wider discussion of scientific literacy,

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[4] For example, early on in the original *Nuffield Physics* course, students are provided with a lever, a fulcrum and some weights (uniform square metal plates) and are invited to 'explore' and to 'find out what you can'. No particular problem is stated; no procedure is recommended. It is assumed that the Law of Moments will simply emerge from undirected, open-ended exploration. Nothing could be further from the truth. First, the system does not balance in the way the students expect because the pivot is below the centre of gravity. If the weights are suspended *below* the pivot, as in a set of scales, the beam will balance. However, there is little chance that children will discover this for themselves. Second, children tend to spread the weights irregularly along the entire length of the beam. The complexity of this arrangement obscures the simple relationship that is sought. Consequently, teachers begin to proffer advice on how to make the problem simpler and to issue instructions about the best way to proceed. Similar things happen whenever children are presented with this kind of open-ended situation. See Hodson (1996) for an extended discussion of these issues.

[5] See, for example, Cawthron and Rowell (1978), Hodson (1985, 1986, 1988a, b, 1990, 1991), Matthews (1991, 1992), Nadeau and Désautels (1984)) and Royal Society (1985).

a term that first appeared in the US educational literature about 50 years ago in papers by Paul Hurd (1958) and Richard McCurdy (1958) and in the Rockefeller Brothers Fund (1958) report *The Pursuit of Excellence*, and is now regarded as a key feature of most science curricula.

Despite the term scientific literacy being enthusiastically adopted by many science educators as a useful slogan or rallying call (see Roberts 1983, 2007), there was little in the way of precise or agreed meaning until Pella et al. (1966) suggested that it comprises an understanding of the basic concepts of science, the nature of science, the ethics that control scientists in their work, the interrelationships of science and society, the interrelationships of science and the humanities and the differences between science and technology. Almost a quarter century later, the authors of *Science for All Americans* (AAAS 1989) drew upon very similar categories to define a scientifically literate person as 'one who is aware that science, mathematics, and technology are interdependent human enterprises with strengths and limitations; understands key concepts and principles of science; is familiar with the natural world and recognizes both its diversity and unity; and uses scientific knowledge and scientific ways of thinking for individual and social purposes' (p. 4). It is significant that these perspectives are now an integral part of the US *National Science Education Standards* (National Research Council 1996) and a central plank of the framework for the *Programme for International Student Assessment* (PISA) studies (OECD 1999, 2006, www.pisa.oecd.org). Detailed review of the literature focused on defining notions of scientific literacy is outside the scope of this chapter,[6] save to note that elements of the history of science, philosophy of science and sociology of science that constitute a satisfactory understanding of the nature of science (NOS) have now become firmly established as a major component of scientific literacy and an important learning objective of science curricula in many countries.[7] Indeed, the promotion of NOS in official curriculum documents has become so prominent that Dagher and BouJaoude (2005) have stated: 'improving students' and teachers' understanding of the nature of science has shifted from a *desirable* goal to being a *central* one for achieving scientific literacy' (p. 378, emphasis added). It follows that all arguments for scientific literacy become arguments for NOS.

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[6] Extensive discussion of the history and evolving definition of scientific literacy can be found in Bybee (1997a, b); Choi et al. (2011), De Boer (2001), Dillon (2009), Feinstein (2011), Gräber and Bolte (1997), Hodson (2008, 2011), Hurd (1998), Laugksch (2000), Lehrer and Schauble (2006), Lemke (2004), Linder et al. (2012), McEneaney (2003), Miller (2000), Norris and Phillips (2003), Norris et al. (2013), Oliver et al. (2001), Roberts (2007), Roth and Calabrese Barton (2004), and Ryder (2001). Teachers' understanding of scientific literacy is explored by Smith et al. (2012).

[7] For example, AAAS (1993), Council of Ministers of Education (1997), Department of Education (RSA) (2002), Goodrum et al. (2000), Millar and Osborne (1998), National Research Council (1996), Organization for Economic Cooperation and Development (1999, 2003), Osborne and Dillon (2008), and UNESCO (1993).

28.2 Arguments for NOS/Scientific Literacy in the School Science Curriculum

Reviewing what they describe as an extensive and diverse literature, Thomas and Durant (1987) identify three major categories of argument for promoting scientific literacy (and, therefore, aspects of NOS understanding): (i) benefits to science, (ii) benefits to individuals and (iii) benefits to society as a whole. Driver and colleagues (1996) contend that in addition to its intrinsic value, NOS understanding enhances learning of science content, generates interest in science and develops students' ability to make informed decisions on socioscientific issues based on careful consideration of evidence, while Erduran and colleagues (2007) argue that NOS knowledge (and the wider HPS understanding subsumed in the notion of scientific literacy) is of immense value to teachers, making them more reflective and more resourceful.

Benefits to science are seen largely in terms of increased numbers of recruits to science-based professions (including medicine and engineering), greater support for scientific, technological and medical research and more realistic public expectations of science. A related argument is that confidence and trust in scientists depend on citizens having some general understanding of what scientists do and how they do it – in particular, about what they choose to investigate, the methods they employ, how they validate their research findings and theoretical conclusions and where, how and to whom they disseminate their work.

Arguments that scientific literacy brings benefits to *individuals* come in a variety of forms. First, it is commonly argued that scientifically literate individuals will have access to a wide range of employment opportunities and are well positioned to respond positively and competently to the introduction of new technologies in the workplace. Second, it is widely assumed that those who are scientifically literate are better able to cope with the demands of everyday life in an increasingly technology-dominated society, better positioned to evaluate and respond appropriately to the scientific evidence and arguments (sometimes authentic and relevant, sometimes biased, distorted, fallacious or irrelevant) used by advertizing agencies and deployed by politicians and better equipped to make important decisions that affect their health, security and economic well-being.

Arguments that enhanced scientific literacy brings benefits to *society as a whole* include the familiar and increasingly pervasive economic argument and the claim that it promotes democracy and responsible citizenship. The first argument sees scientific literacy as a form of human capital that builds, sustains and develops the economic well-being of a nation. Put simply, continued economic development brought about by enhanced competitiveness in international markets (regarded as incontrovertibly a 'good thing') depends on science-based research and development, technological innovation and a steady supply of scientists, engineers and technicians. The case for scientific literacy as a means of enhancing democracy and responsible citizenship is just as strongly made as the economic argument, though by a very different assembly of stakeholders and interest groups. In the words of Chen and Novick (1984), enhanced scientific literacy (and its attendant components of NOS understanding) is a means 'to avert the situation where social values, individual involvement, responsibility, community participation and the very heart of democratic decision making will be dominated and practiced by a small elite' (p. 425).

This line of argument maintains that democracy is strengthened when *all* citizens are equipped to confront and evaluate socioscientific issues (SSI) knowledgeably and rationally, as well as emotionally, and are enabled to make informed decisions on matters of personal and public concern. Those who are scientifically illiterate are in many ways disempowered and excluded from active civic participation. For these reasons, Tate (2001) declares that access to high-quality science education, with its increasing emphasis on NOS, is a civil rights issue. Of course, as both Levinson (2010) and Tytler (2007) remind us, the notion of science education for citizenship raises a whole raft of questions about the kind of citizen and the kind of society we have in mind and about what constitutes *informed* and *responsible* citizenship – matters well outside the scope of this chapter.

A number of writers have claimed, somewhat extravagantly, that appreciation of the ethical standards and code of responsible behaviour that the scientific community seeks to impose on practitioners will lead to more ethical behaviour in the wider community – that is, the pursuit of scientific truth regardless of personal interests, ambitions and prejudice (part of the traditional image of the objective and dispassionate scientist) makes science a powerful carrier of moral values and ethical principles: 'Science is in many respects the systematic application of some highly regarded human values – integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, and imagination' (AAAS 1989, p. 201). Shortland (1988) summarizes this rationale as follows: 'the internal norms or values of science are so far above those of everyday life that their transfer into a wider culture would signal a major advance in human civilization' (p. 310). The authors of *Science for All Americans* (AAAS 1989) present a similar argument: 'Science is in many respects the systematic application of some highly regarded human values – integrity, diligence, fairness, curiosity, openness to new ideas, skepticism, and imagination' (p. 201). Studying science, scientists and scientific practice will, they argue, help to instill these values in students. In other words, scientific literacy doesn't just result in more skilled and more knowledgeable people, it results in *wiser* people, that is, people well-equipped to make morally and ethically superior decisions. Whether contemporary scientific practice does impose and instill these values is discussed later in the chapter.

28.3 Establishing NOS Priorities

Once the lens of NOS became focused on the school science curriculum, it was quickly apparent that whatever confused and confusing views of science are held by students are compounded by conventional science education. There are particularly powerful messages about science embedded in all teaching and learning activities, especially laboratory activities. These messages too often convey distorted or over-simplified views of the nature of scientific investigations, especially with respect to the role of theory. These 'folk theories' of science, as Windschitl (2004) calls them, are also held by teachers (as a consequence of their own science education) and have substantial influence on their day-to-day curriculum decision-making, thus reinforcing similar messages embedded in school science textbooks and other curriculum materials.

As part of a major survey of Canadian science education conducted by the Science Council of Canada, Nadeau and Désautels (1984) identified what they called five mythical values stances suffusing science education:

- *Naïve realism* – science gives access to truth about the universe.
- *Blissful empiricism* – science is the meticulous, orderly and exhaustive gathering of data.
- *Credulous experimentation* – experiments can conclusively verify hypotheses.
- *Excessive rationalism* – science proceeds solely by logic and rational appraisal.
- *Blind idealism* – scientists are completely disinterested, objective beings.

The cumulative message is that science has an all-purpose, straightforward and reliable method of ascertaining the truth about the universe, with the certainty of scientific knowledge being located in objective observation, extensive data collection and experimental verification. Moreover, scientists are rational, logical, open-minded and intellectually honest people who are required, by their commitment to the scientific enterprise, to adopt a disinterested, value-free and analytical stance. In Cawthron and Rowell's (1978) words, the scientist is regarded by the science curriculum as 'a depersonalized and idealized seeker after truth, painstakingly pushing back the curtains which obscure objective reality, and abstracting order from the flux, an order which is directly revealable to him through a distinctive scientific method' (p. 32). While much has changed in the intervening years, many school science curricula and school textbooks continue to project these images.[8] For example, Loving (1997) laments that all too often

> (a) science is taught totally ignoring what it took to get to the explanations we are learning – often with lectures, reading text, and memorizing for a test. In other words, it is taught free of history, free of philosophy, and in its final form. (b) Science is taught as having one method that all scientists follow step-by-step. (c) Science is taught as if explanations are the truth – with little equivocation. (d) Laboratory experiences are designed as recipes with one right answer. Finally, (e) scientists are portrayed as somehow free from human foibles, humor, or any interests other than their work. (p. 443)

At about the same time, Hodson (1998) identified ten common myths and falsehoods promoted, sometimes explicitly and sometimes implicitly, by the science curriculum: observation provides direct and reliable access to secure knowledge;

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[8] Abd-El-Khalick (2001), Abd-El-Khalick et al. (2008), Clough (2006), Cross (1995), Knain (2001), Kosso (2009), Lakin and Wellington (1994), McComas (1998), van Eijck and Roth (2008) and Vesterinen et al. (2011).

science always starts with observation; science always proceeds by induction; science comprises discrete, generic processes; experiments are decisive; scientific inquiry is a simple algorithmic procedure; science is a value-free activity; science is an exclusively Western, post-Renaissance activity; the so-called scientific attitudes are essential to the effective practice of science; and all scientists possess these attitudes. A broadly similar list of falsehoods was generated by McComas (1998) from his critical reading of science textbooks: hypotheses become theories that in turn become laws; scientific laws and other such ideas are absolute; a hypothesis is an educated guess; a general and universal scientific method exists; evidence accumulated carefully will result in sure knowledge; science and its methods provide absolute proof; science is procedural more than creative; science and its methods can answer all questions; scientists are particularly objective; experiments are the principal route to scientific knowledge; scientific conclusions are reviewed for accuracy; acceptance of new scientific knowledge is straightforward; science models represent reality; science and technology are identical; and science is a solitary pursuit. In quite startling contrast, Siegel (1991) states that

> Contemporary research… has revealed a more accurate picture of the scientist as one who is driven by prior convictions and commitments; who is guided by group loyalties and sometimes petty personal squabbles; who is frequently quite unable to recognize evidence for what it is; and whose personal career motivations give the lie to the idea that the scientist yearns only or even mainly for the truth. (p. 45)

Two questions spring to mind. First, is this a more authentic portrayal of scientific practice? Second, is it an appropriate view for the school science curriculum? Sweeping away an old and (for some) discredited view is one thing; finding an acceptable set of alternatives is somewhat different. Finding a list appropriate for the school curriculum is even more difficult. Many science educators will share Israel Scheffler's alarm at some of the alternatives that have been advanced:

> The extreme alternative that threatens is the view that theory is not controlled by data, but that data are manufactured by theory; that rival hypotheses cannot be rationally evaluated, there being no neutral court of observational appeal nor any shared stock of meanings; that scientific change is a product not of evidential appraisal and logical judgment, but of intuition, persuasion and conversion; that reality does not constrain the thought of the scientist but is rather itself a projection of that thought. (Scheffler 1967, p. v)

Longbottom and Butler (1999) express similar concerns when they state that 'if we go along with those who deny that modern science provides a privileged view of the world… we fall into an abyss where skeptical postmodernists, who have lost faith in reason, dismiss all knowledge claims as equally arbitrary and assume the universe to be unreliable in its behavior and incapable of being understood' (p. 482). Stanley and Brickhouse (1995) regard such remarks as examples of what Bernstein (1983) called 'Cartesian anxiety': the fear that if we do not retain our belief in the traditional objective foundations of scientific method we have no rational basis for making any knowledge claims. In short, fear that belief in scientific *progress* will be replaced by scientific *change* consequent upon power struggles among competing groups, with 'victory' always going to the better resourced. Fear that scientific knowledge is no longer to be regarded as the product of a rigorous method or set of methods; instead, it is merely the way a particular influential group of scientists happens to think and can persuade, cajole or coerce others into accepting.

In building a school science curriculum, are we faced with a stark choice between the traditional and the postmodern? Are we required to choose between the image of a scientist as a cool, detached seeker-after-truth patiently collecting data from which conclusions will eventually be drawn, when all the evidence is in hand, and that of 'an agile opportunist who will switch research tactics, and perhaps even her entire agenda, as the situation requires' (Fuller 1992, p. 401). Which view is the more authentic? Equally important, what should we tell students? What is in their interests? Some years ago, Stephen Brush (1974) posed the question: 'should the history of science should be rated X?' The question is just as pertinent to the philosophy of science and the sociology of science. Should we expose students to the anarchistic epistemology of Paul Feyerabend? Should we lift the lid off the Pandora's Box that is the sociology of science? Would students be harmed by too early an exposure to these views? When we seek to question (and possibly reject) the certainties of the traditional view of science, are we left with no firm guidance, no standards and no shared meaning? Does recognition of the sociocultural baggage of science entail regarding science as just one cultural artefact among many others, with no particular claim on our allegiance? Is any kind of compromise possible between these extremes and among this diversity? Can we retain what is still good and useful about the old view of science (such as conceptual clarity and stringent testing) while embracing what is good and useful in the new (such as sensitivity to sociocultural dynamics and awareness of the possibility of error, bias, fraud and the misuse of science)? Can the curriculum achieve a balance that is acceptable to most stakeholders? In short, what particular items from all the argument and counter argument would constitute an educationally appropriate and teachable selection? Later discussion touches on the age appropriateness of a number of NOS items, while attention at this point focuses on whether there is any nature of science understanding that can be taken for granted and regarded as no longer in dispute. Is there any consensus among scholars about an acceptable alternative to the traditional view that will allay the fears expressed by Scheffler and others?

Responses to a 20-item Likert-type questionnaire on '15 tenets of NOS' led Alters (1997a, b) to conclude that *there is no consensus* – at least, not among the 210 philosophers of science he surveyed. In the words of Laudan and colleagues (1986),

> The fact of the matter is that we have no well-confirmed general picture of how science works, no theory of science worthy of general assent. We did once have a well developed and historically influential philosophical position, that of positivism or logical empiricism, which has by now been effectively refuted. We have a number of recent theories of science which, while stimulating much interest, have hardly been tested at all. And we have specific hypotheses about various cognitive aspects of science, which are widely discussed but wholly undecided. If any extant position does provide a viable understanding of how science operates, we are far from being able to identify which it is. (p. 142)

Interestingly, despite this categorical denial of any consensus, it seems that the authors of several important science curriculum reform documents (AAAS (1989, 1993) and NRC (1996), among others) seem to be in fairly substantial agreement on the elements of NOS that should be included in the school science curriculum (McComas and Olson 1998):

- Scientific knowledge is tentative.
- Science relies on empirical evidence.
- Observation is theory laden.
- There is no universal scientific method.
- Laws and theories serve different roles in science.
- Scientists require replicability and truthful reporting.
- Science is an attempt to explain natural phenomena.
- Scientists are creative.
- Science is part of social tradition.
- Science has played an important role in technology.
- Scientific ideas have been affected by their social and historical milieu.
- Changes in science occur gradually.
- Science has global implications.
- New knowledge must be reported clearly and openly.

In an effort to shed further light on this matter, Osborne and colleagues (2003) conducted a Delphi study to ascertain the extent of agreement among 23 participants drawn from the 'expert community' on what ideas about science should be taught in school science. The participants included five scientists, five persons categorized as historians, philosophers and/or sociologists of science, five science educators, four science teachers and four science communicators. Although there was some variation among individuals, there was broad agreement on nine major themes: scientific method and critical testing, scientific creativity, historical development of scientific knowledge, science and questioning, diversity of scientific thinking, analysis and interpretation of data, science and certainty, hypothesis and prediction, and cooperation and collaboration. A comparison of these themes with those distilled from the science education standards documents in McComas and Olson's (1998) study reveals many similarities. A broadly similar but shorter list that has gained considerable currency among science educators can be found in Lederman and colleagues (2002): scientific knowledge is tentative, empirically based, subjective (in the sense of being theory dependent and impacted by the scientists' experiences and values), socioculturally embedded and, in part, the product of human imagination and creativity.

28.4 Some Problems with the Consensus View

Useful as consensus can be in assisting curriculum planning and the design of assessment and evaluation schemes, a number of questions should be asked. For example, is the apparent consensus deliberately pitched at such a trivial level that nobody could possibly quibble with it? Most of the items in the list are not specific to science, either individually or collectively. All human knowledge is tentative;

all forms of knowledge building are creative. This is not to say that these characteristics are not applicable to science; but it is to say that they do not distinguish it from several other human activities. It is the sheer banality and unhelpfulness of some of the items that many teachers find frustrating. For example, statements such as 'science is an attempt to explain natural phenomena' and 'science has played an important role in technology' – items in the consensus list developed by McComas et al. (1998) – do not claim anything particularly insightful or helpful for students trying to understand what science is all about. Of course, some would argue that a list of relatively trivial items is better than no list at all. Perhaps it is, although items in the consensus list can sometimes be very puzzling or even irrelevant to an understanding of scientific practice and the capacity to function as a scientist. For example, several writers who advocate the consensus view also argue that students should understand the functions of and relationships between theories and laws and draw a distinction between observation and inference. Drawing a distinction between laws and theories is certainly not a high priority for practising scientists, as informants in the study conducted by Wong and Hodson (2009) pointed out very clearly. As far as students are concerned, one is led to wonder in what ways knowledge of a supposed difference between a law and a theory would help them to make decisions on where they stand in relation to controversial socioscientific issues.

The naïve proposition that there is a crucial distinction between observation and inference is singularly unhelpful to students trying to make sense of contemporary technology-supported investigative work. Superficially the distinction sounds fine and seems to accord with what we consider to be good practice in scientific inquiry: having respect for the evidence and not claiming more than the data can justify. However, closer examination in the light of the theory-laden nature of scientific observation suggests that the supposed demarcation is not always as clear as some would claim. When a new theory appears or when new scientific instruments are developed, our notion of what counts as an observation and what counts as an inference may change. As Feyerabend (1962) points out, observation statements are merely those statements about phenomena and events to which we can assent quickly, relatively reliably and without calculation or further inference because we all accept, without question, the theories on which they are based. Thus, where individuals draw the line between observation and inference reflects the sophistication of their scientific knowledge, their confidence in that knowledge and their experience and familiarity with the phenomena or events being studied. When theories are not in dispute, when they are well understood and taken for granted, the theoretical language *is* the observation language, and we use theoretical terms in making and reporting observations. Terms like *reflection* and *refraction*, *conduction* and *nonconduction*, and *melting, dissolving* and *subliming*, all of which are used regularly in school science as observation terms, carry a substantial inferential component rooted in theoretical understanding. The key point is that unless some theories are taken for granted (and deemed to be no longer in dispute) and unless theory-loaded terms are used for making observations, we can never make progress. We would forever be trying to retreat to the raw data, to some position that we could regard as theory-free.

Too literal an interpretation of statements about the tentative nature of science can be counterproductive, leading students to regard *all* science as no more than temporary (Harding and Hare 2000). Scientific knowledge is tentative because it is based, ultimately, on empirical evidence that may be incomplete and because it is collected and interpreted in terms of current theory – theory that may eventually be changed as a consequence of the very evidence that is collected. In all these endeavours, the creative imagination of individual scientists is impacted by all manner of personal experiences and values. Moreover, the collective wisdom of the scientific community that supports the practice, scrutinizes the procedures and evaluates the products is also subject to complex sociopolitical, economic and moral-ethical forces. In consequence, there can be no certainty about the knowledge produced. However, to admit that absolute truth is an impossible goal is not to admit that we are uncertain about everything. We *know* many things about the universe even though we recognize that many of our theoretical systems are still subject to revision, or even rejection.

Regarding the issue of tentativeness, there are several closely related issues to consider. First, very specific claims about phenomena and events may be regarded as 'true' (in a scientific sense) even though the theories that account for the events are regarded as tentative. Because the whole necessarily extends beyond the parts of which it is comprised, the whole may be seen as tentative while the parts (or some of them) are regarded as certain. Most theories are tentative when first developed, but are accepted as true when they have been elaborated, refined and successfully used and when they are consistent with other theories and strongly supported by evidence. Teachers make a grave mistake when they encourage students to regard all science as tentative. Indeed, if scientists did not accept some knowledge as well established, we would be unable to make progress.

We should also ask whether the consensus list includes consideration of the 'big issues' with which philosophers of science have traditionally grappled. Apparently not, according to Abd-El-Khalick and BouJaoude (1997), Abd-El-Khalick, Bell and Lederman (1998) and Lederman et al. (2002), who state that while philosophers and sociologists might disagree on some aspects of NOS, these disagreements are irrelevant to K-12 students and their teachers. Many other scholars would disagree. Some of these disputes focus on the most interesting features of science, for example, the status of scientific knowledge in terms of realism and instrumentalism, the extent to which science is socially constructed/determined and the nature of scientific rationality. Another major concern with the consensus view is that it promotes a static picture of science and fails to acknowledge important differences among the sciences. In reality, the practices and procedures of science change over time. As a particular science progresses and new theories and procedures are developed, the nature of scientific reasoning changes. Indeed, we should seriously question whether views in the philosophy of science that were arrived at some years ago can any longer reflect the nature of twenty-first-century science, especially in rapidly developing fields such as genetics and molecular biology, where there is now substantial research related to the generation of data and subsequent data mining (e.g. generation of genomic sequences of a number of living things) rather than the kind of hypothesis-driven inquiry promoted by the consensus view – developments that are, of course, driven by technological advances.

In a little known but very insightful and educationally significant article, Michael Clough (2007) urges teachers to shift emphasis away from teaching the ‘tenets of NOS’, because they are easily misinterpreted, oversimplified and become something to be memorized rather than understood and utilized, and towards asking important questions such as the following: In what sense is scientific knowledge tentative and in what sense is it durable? To what extent is scientific knowledge socially and culturally embedded? In what sense does it transcend society and culture? How are observations and inferences different? In what sense can they not be differentiated? A recent essay by Michael Matthews (2012) subjects the consensus view (specifically, the ‘Lederman Seven’, as he calls it) to rigorous critical scrutiny, concluding that the items need to be ‘much more philosophically and historically refined and developed’ (p. 12) if they are to be genuinely useful to teachers and their students. As a way forward, he advocates a shift of terminology and research focus from the ‘essentialist and epistemologically focussed ‘Nature of Science’ (NOS) to a more relaxed, contextual and heterogeneous ‘Features of Science’ (FOS)’ (p. 4). Such a change, he argues, would avoid many of the pitfalls and shortcomings of current research and scholarship in the field – in particular, the confused conflation of epistemological, sociological, psychological, ethical, commercial and philosophical aspects of science into a single list of items to be taught and assessed, the avoidance of debate about contentious issues in HPS, the neglect of historical perspective and the failure to account for significant differences in approach among the sciences. In response to this and other criticism, Lederman, Antinck and Bartos (2012) state ‘We (my colleagues and fellow researchers) *are not* advocating a definitive or universal definition of the construct [of NOS]. We have never advocated that that our “list” is *the* only list/definition… What we prefer readers to focus on are the understandings we want students to have. The understandings need not be limited to those we have selected’ (p. 2).

28.5 Diversity Among the Sciences

Many philosophers of science hold that there is no universal nature of science because the sciences themselves have no unity. The best that can be said is that there is a ‘family resemblance among the sciences’ (Wittgenstein 1953), with common interests and some areas of methodological and conceptual agreement – what Loving (1997) calls a ‘loose configuration of critical processes and conceptual frameworks, including various methods, aims, and theories all designed to shed light on nature’ (p. 437). The consensus view specifically disallows consideration of diversity among the sciences and chooses to disregard the substantial differences between the day-to-day activities of palaeontologists and epidemiologists, for example, or between scientists researching in high energy physics and those engaged in molecular biology. There are significant differences among the subdisciplines of science in terms of the kind of research questions asked, the methods and technologies employed to answer them, the kind of evidence sought, the extent to which they use experimentation, the ways in which data for theory building are collected, the standards by which investigations and conclusions are judged and the kinds of arguments deployed. Jenkins (2007) puts it succinctly when he says that 'the criteria for deciding what counts as evidence, and thus the nature of an explanation that relies upon that evidence, may also be different' (p. 225). There are substantial differences in the extent to which mathematics is deployed (Knorr-Cetina 1999), and there may even be differences, as Cartwright (1999) notes, in the values underpinning the enterprise. In other words, the specifics of scientific rationality change between subdisciplines, with each subdiscipline playing the game of science according to its own rules, a view discussed at some length in Hodson (2008, 2009).

Like Sandra Harding (1986), Ernst Mayr (1988, 1997, 2004) has criticized the standard or consensus NOS views promoted in many curriculum documents on grounds that they are nearly always derived from physics. Biology, he argues, is markedly different in many respects, not the least significant of which is that many biological ideas are not subject to the kind of falsificationist scrutiny advocated by Karl Popper (1959) and given such prominence in school science textbooks: 'It is particularly ill-suited for the testing of probabilistic theories, which include most theories in biology… And in fields such as evolutionary biology… it is often very difficult, if not impossible, to decisively falsify an individual theory' (Mayr 1997, p. 49).

The procedures of investigation in a particular subdiscipline of science are deeply grounded in the field's substantive aspects and the specific purposes of the inquiry. For example, while physicists may spend time designing critical experiments to test daring hypotheses, as Popper (1959) states, most chemists are intent on synthesizing new compounds:

> Chemists make molecules. They do other things, to be sure – they study the properties of these molecules; they analyze… they form theories as to why molecules are stable, why they have the shapes or colors that they do; they study mechanisms, trying to find out how molecules react. But at the heart of their science is the molecule that is made, either by a natural process or by a human being. (Hoffmann 1995, p. 95)

Moreover, as a particular science progresses and new theories and procedures are developed, the nature of scientific reasoning may change. Indeed, Mayr (1988, 2004) has distinguished two different fields even within biology: *functional* or mechanistic biology and *evolutionary* biology, distinguished by the type of causation addressed. Functional biology addresses questions of proximate causation; evolutionary biology addresses questions of ultimate causation:

> The functional biologist is vitally concerned with the operation and interaction of structural elements, from molecules up to organs and whole individuals. His ever-repeated question is 'How?'… The evolutionary biologist differs in his method and in the problems in which he is interested. His basic question is 'Why?' (Mayr 1988, p. 25)

In similar vein, Ault (1998) argues that the geosciences are fundamentally historical and interpretive, rather than experimental. The goal of geological inquiry, he argues, is interpretation of geologic phenomena based on observations, carefully warranted inferences and integration or reconciliation of independent lines of inquiry, often conducted in diverse locations. These interpretations result in a description of historical sequences of events, *sometimes* accompanied by a causal model.

Elby and Hammer (2001) argue that the widely adopted consensus list of NOS items is too general and too broad and that it is neither philosophically valid nor productive of good learning of science: 'a sophisticated epistemology does not consist of blanket generalizations that apply to all knowledge in all disciplines and contexts; it incorporates contextual dependencies and judgments' (p. 565). Essentially the same point is made by Clough (2006) when he says that 'while some characteristics [of NOS] are, to an acceptable degree uncontroversial… most are contextual, with important and complex exceptions' (p. 463). In short, the differences in approach are just too extensive and too significant to be properly accounted for by generic models of inquiry. Instead of trying to find and promote broad generalizations about the nature of science, scientific inquiry and scientific knowledge, a position recently given renewed emphasis by Abd-El-Khalick (2012), teachers should be building an understanding of NOS from examples of the daily practice of diverse groups of scientists engaged in diverse practices and should be creating opportunities for students to experience, explore and discuss the differences in knowledge and its generation across multiple contexts. It is for this reason that NOS-oriented research needs to study the work of scientists active at the frontier of knowledge generation (Schwartz and Lederman 2008; Wong and Hodson 2009, 2010). Student understanding of the complexity and diversity of scientific practice would be immeasurably helped by adoption of the notion of a 'family resemblance' among the sciences, as in Irzik and Nola's (2011) organization of the cognitive aspects of science into four categories: (i) *activities* (planning, conducting and making sense of scientific inquiries), (ii) *aims and values*, (iii) *methodologies and methodological rules*, and (iv) *products* (scientific knowledge) (see also Nola and Irzik 2013). These four categories of cognitive aspects could and perhaps should be extended to accommodate the noncognitive institutional and social norms which are operative within science and influence science (see below).

In brief, it is time to replace the consensus view of NOS, useful though it has been in promoting the establishment of NOS in the school science curriculum, with a philosophically more sophisticated and more authentic views of scientific practice, as advocated by Elby and Hammer (2001), Hodson (2008, 2009), Matthews (2012), Rudolph (2000) and Wong and Hodson (2013). Interestingly, children regard diversity of approach in scientific investigations as inevitable. They have no expectations of a particular method; it is the teachers who create the expectation of a single method through their continual reference to *the* scientific method (Hodson 1998) and, by extension, establish the belief that there are particular and necessary attributes (the so-called scientific attitudes) for engaging in it.

28.6 Some Recent NOS-Oriented Initiatives

The past decade has seen a remarkable growth in research and curriculum development in two important NOS-related areas: *scientific argumentation* and *modelling*. Both these aspects of NOS (as defined at the beginning of this chapter) warrant some attention here. My concerns relate to both students' knowledge of these processes as used by scientists and the development of their ability to use them appropriately and productively for themselves.

What is often unrecognized by science teachers, science textbooks and curricula, and by the wider public, is that *dispute* is one of the key driving forces of science. Real science is impregnated with claims, counter claims, argument and dispute. Arguments concerning the appropriateness of experimental design, the interpretation of evidence and the validity of knowledge claims are located at the core of scientific practice. Arguments are used to address problems, resolve issues and settle disputes. Moreover, our day-to-day decision-making with regard to socioscientific issues is based largely on the evaluation of information, arguments, conclusions, views, opinions and reports made available via newspapers, magazines, television, radio and the Internet. Citizens need to know the kinds of knowledge claims that scientists make and how they advance them. They need to understand the standards, norms and conventions of scientific argumentation in order to judge the rival merits of competing arguments and engage meaningfully in debate on SSI. In particular, they need a robust understanding of the form, structure and language of scientific arguments, the kind of evidence invoked, how it is organized and deployed and the ways in which theory is used and the work of other scientists cited to strengthen a case.

Neglect of scientific argumentation in the school science curriculum gives the impression that science is the unproblematic accumulation of data and theory. In consequence, students are often puzzled and may even be alarmed by reports of disagreements among scientists on matters of contemporary importance. They may be unable to address in a critical and confident way the claims and counter claims impregnating the SSI with which they are confronted in daily life. A number of science educators have recently turned their attention to these matters and to what had previously been a shamefully neglected area of research and curriculum development.[9] The research agenda focuses on the following questions: Why is argumentation important? What are the distinctive features of scientific argumentation? How can it be taught? What strategies are available? To what extent and in what

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[9] For example, Arduriz Bravo (2013), Berland and Hammer (2012), Berland and Lee (2012), Berland and McNeill (2010), Berland and Reiser (2009, 2011), Böttcher and Meisertt (2011), Bricker and Bell (2008), Driver et al. (2000), Duschl (2008), Duschl and Osborne (2002), Erduran et al. (2004), Evagorou and Osborne (2013), Ford and Wargo (2012), Jiménez-Aleixandre and Erduran (2008), Khishfe (2012a), Kuhn (2010), Newton et al. (1999), Nielsen (2012a, b, 2013), Osborne (2001), Osborne and Patterson (2011), Osborne et al. (2004), Passmore and Svoboda (2012), Pluta et al. (2011), Sampson and Clark (2008, 2011), Sampson and Blanchard (2012), Sampson and Walker (2012), Sampson et al. (2011), Sandoval and Cam (2011), Sandoval and Millwood (2005, 2008), Simon et al. (2006), and Ryu and Sandoval (2012)

ways are the strategies successful? What problems arise and how can the difficulties be overcome? This research is discussed at length in Hodson (2009).

Another significant NOS-related growth area in recent years has been the focus on models and modelling. Because scientific literacy entails a robust understanding of a wide range of scientific ideas, principles, models and theories, students need to know something of their origin, scope and limitations; understand the role of models in the design, conduct, interpretation and reporting of scientific investigations; and recognize the ways in which a complex of cognitive problems and factors related to the prevailing sociocultural context influenced the development of key ideas over time. They also need to experience model building for themselves and to give and receive criticism in their own quest for better models. As Matthews (2012) comments, 'It is difficult to think of science without models' (p. 19).

The nature of mental models has long been an area of research in cognitive psychology, dating back to the seminal work of Johnson-Laird (1983) and Gentner and Stevens (1983), but in recent years, the topic of models and modelling has generated considerable interest among science educators.[10] This interest can be categorized into three principal areas of concern: the particular models and theories produced by scientists as explanatory systems, including the history of their development; the ways in which scientists utilize models as cognitive tools in their day-to-day problem solving, theory articulation and theory revision; and the role of models and modelling in science pedagogy.

The emergence of curricula oriented towards the consideration of socioscientific issues (SSI), in which NOS plays a key role, is discussed later in the chapter.

28.7 Assessing NOS Understanding

Given the perennial concern of education policy makers with assessment and accountability measures and the need for teachers to ascertain students' knowledge and understanding both prior to and following instruction, there has been a long-standing interest in researching students' NOS views. Also, given the commonsense understanding that teachers' views will inevitably and profoundly impact the kind of teaching and learning experiences they provide, interest has been high in ascertaining

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[10] Bamberger and Davis (2013), Clement and Rea-Ramirez (2008), Coll (2006), Coll and Taylor (2005), Coll and Treagust (2002, 2003a, b), Coll et al. (2005), Davies and Gilbert (2003), Duschl and Grandy (2008), Erduran and Duschl (2004), Franco et al. (1999), Gilbert (2004), Gilbert and Boulter (1998, 2000), Gilbert et al. (1998a, b), Gobert and Pallant (2004), Gobert et al. (2011), Greca and Moreira (2000, 2002), Halloun (2004, 2007), Hansen et al. (2004), Hart (2008), Justi and Gilbert (2002a, b, c, 2003), Justi and van Driel (2005), Kawasaki et al. (2004), Khan (2007), Koponen (2007), Lehrer and Schauble (2005), Lopes and Costa (2007), Maia and Justi (2009), Manz (2012), Nelson and Davis (2012), Nersessian (2008), Oh and Oh (2011), Perkins and Grotzer (2005), Russ et al. (2008), Saari and Viiri (2003), Shen and Confrey (2007), special issue of *Science & Education* (2007, 16, issues 7–8), Svoboda et al. (2013), Taber (2003), Taylor et al. (2003), Treagust et al. (2002, 2004), and van Driel and Verloop (1999)

teachers' NOS views. Given suitable modification in terms of language and theoretical sophistication, the two tasks can utilize many of the same instruments.

Methods employed include questionnaires and surveys, interviews, small group discussions, writing tasks and classroom observations (particularly in the context of hands-on activities). Each has its strengths and weaknesses. Necessarily, researchers who use questionnaire methods must decide what counts as legitimate research data *before* the data collection process begins; those who use classroom observation (and, to a lesser extent, those who use interview methods) are able to make such decisions *during* or *after* data collection. They also have the luxury of embracing multiple perspectives and can readily update their interpretive frameworks to take account of changes in our understanding in history, philosophy and sociology of science.

More than 30 years ago, a review by Mayer and Richmond (1982) listed 32 NOS-oriented assessment instruments, among the best known of which are the *Test on Understanding Science* (TOUS) (Cooley and Klopfer 1961), the *Nature of Science Scale* (NOSS) (Kimball 1967), the *Nature of Science Test* (NOST) (Billeh and Hasan 1975) and the *Nature of Scientific Knowledge Scale* (NSKS) (Rubba 1976; Rubba and Anderson 1978), together with a modified version (M-NSKS) developed by Meichtry (1992). Instruments dealing with the processes of science, such as the *Science Process Inventory* (SPI) (Welch 1969a), the *Wisconsin Inventory of Science Processes* (WISP) (Welch 1969b) and the *Test of Integrated Process Skills* (TIPS) (Burns et al. 1985; Dillashaw and Okey 1980) could also be regarded as providing valuable information on some key aspects of NOS.

While questionnaires are the most commonly used research methods, largely because they are quick and easy to administer, they can be overly restrictive, incapable of accommodating subtle shades of meaning and susceptible to misinterpretation. Sometimes the complexity and subtlety of NOS issues makes it difficult to find appropriate language for framing questions. If it is difficult for the researcher to find the right words, how much more difficult is it for the respondent to capture the meaning they seek to convey? It cannot be assumed that the question and/or the answer will be understood in exactly the way it was intended, especially by younger students and those with poor language skills. Multiple-choice items and other objective instruments leave little or no scope for expressing doubt or subtle shades of difference in meaning and rarely afford respondents the opportunity to explain *why* they have made a particular response to a questionnaire item. It may even be that the same response from two respondents arises from quite different understanding and reasoning, while similar reasoning by two respondents results in different responses.

Further, many instruments are constructed in accordance with a particular philosophical position and are predicated on the assumption that all scientists think and behave in the same way. Hence, teacher and/or student responses that do not correspond to the model of science assumed in the test are judged to be 'incorrect', 'inadequate' or 'naïve'. Alters (1997a, b), Koulaidis and Ogborn (1995), Lucas (1975) and Lederman et al. (2002) provide extended discussions of this issue. It is also the case that many of the early instruments predated significant work in the philosophy and sociology of science, and so are of severely limited value in contemporary studies. Reviews by Lederman (1992, 2007), Lederman et al. (1998, 2000, 2013) describe several NOS instruments that take into account the work of more recent and even contemporary scholars in the philosophy and sociology of science, including *Conceptions of Scientific Theories Test* (COST) (Cotham and Smith 1981), *Views on Science-Technology-Society* (VOSTS) (Aikenhead et al. 1989), the *Nature of Science Survey* (Lederman and O'Malley 1990), the *Nature of Science Profile* (Nott and Wellington 1993) and the *Views of Nature of Science Questionnaire* (VNOS) (Lederman et al. 2002) and its several subsequent modifications (see Flick and Lederman 2004; Lederman 2004, 2007; Schwartz and Lederman 2008). A recent review by Deng and colleagues (2011) reports and critiques 105 research studies of students' NOS views, using a wide range of instruments, though lack of space precludes discussion here. Constraints on space also preclude discussion of the recent critical review by Guerro-Ramos (2012) of research approaches for ascertaining teachers' views of NOS and their relevance to classroom decision-making.

The designers of VOSTS attempted to circumvent some of the common questionnaire design problems identified by psychometricians by constructing a number of different 'position statements' (sometimes up to ten positions per item) derived from student writing and interviews, including 'I don't understand' and 'I don't know enough about this subject to make a choice' (Aikenhead et al. 1987; Aikenhead and Ryan 1992). It is the avoidance of the forced choice and the wide range of aspects covered (definitions, influence of society on science/technology, influence of science/technology on society, characteristics of scientists, social construction of scientific knowledge, social construction of technology, nature of scientific knowledge, and so on) that give the instrument its enormous research potential. Lederman and O'Malley (1990) utilized some of the design characteristics of VOSTS to develop the *Nature of Science Survey*, an instrument comprising just seven fairly open-ended items (e.g. 'Is there a difference between a scientific theory and a scientific law? Give an example to illustrate your answer'), to be used in conjunction with follow-up interviews to further explore and clarify students' responses.

At present, the most widely used and most extensively cited contemporary instrument for ascertaining students' NOS views is the *Views of Nature of Science Questionnaire* (VNOS). While it has provided much valuable information on both students' and teachers' NOS views, it suffers from all the drawbacks attending the so-called consensus view of NOS, as discussed earlier. The *Views on Science and Education* (VOSE) questionnaire, developed by Chen (2006) for use with preservice teachers, focuses on the same seven NOS elements as VNOS (tentativeness of scientific knowledge; nature of observation; scientific methods; hypotheses, laws and theories; imagination; validation of scientific knowledge; objectivity and subjectivity in science) but seeks to address some perceived weaknesses of VOSTS – principally, the overgeneralization and ambiguity of some items and its failure to fully ascertain the reasons underlying a respondent's choice of response. It also seeks to accommodate differences in student teachers' views about what science is likely to be in practice and what science ought to be and to distinguish between NOS views they hold and NOS views they seek to teach.

As Abd-El-Khalick and BouJaoude (1997) point out, VOSTS was conceived and written within a North American sociocultural context and, in consequence, may have limited validity in non-Western contexts. In response to such concerns, Tsai and Liu (2005) have developed a survey instrument that is more sensitive to sociocultural influences on science and students' views of science. It focuses on five characteristics of scientific knowledge and its development: (i) the role of social negotiations within the scientific community; (ii) the invented and creative nature of science; (iii) the theory-laden nature of scientific investigation; (iv) cultural influences on science; and (v) the changing and tentative nature of scientific knowledge. Rooted in similar concerns about the socioculturally determined dimensions of NOS understanding is the *Thinking about Science* instrument designed by Cobern and Loving (2002) as both a pedagogical tool (for preservice teacher education programmes) and a research tool for assessing views of science in relation to economics, the environment, religion, aesthetics, race and gender.

Before leaving this brief survey of questionnaire instruments, it is important to draw attention to the *Views of Scientific Inquiry* questionnaire (Schwartz et al. 2008), which speaks directly to the problems of NOS definition discussed at the beginning of this chapter and is designed to gather information on students' understanding of some key elements of NOS, including (i) scientific investigations are guided by questions and theoretical perspectives; (ii) there are multiple purposes for scientific inquiry and multiple methods for conducting them; (iii) there is an important distinction between data and evidence; (iv) the validation of scientific knowledge involves negotiation of meaning and achievement of consensus; and (v) scientific inquiry is embedded within multiple communities, each with its own standards, values and practices.

28.8 Alternatives to Questionnaires

Frustrated by the seemingly intractable problems of designing effective questionnaires, some researchers and teachers incline to the view that more useful information can be obtained, especially from younger students, by use of open-ended methods such as the Draw-a-Scientist Test (DAST) (Chambers 1983). In his initial study, Chambers used this test with 4,807 primary (elementary) school children in Australia, Canada and the United States. He identified seven common features in their drawings, in addition to the almost universal representation of the scientist as a man: laboratory overall; spectacles (glasses); facial hair; 'symbols of research' (specialized instruments and equipment); 'symbols of knowledge' (books, filing cabinets, etc.); technological products (rockets, medicines, machines); and captions such as 'Eureka' (with its attendant lighted bulb) and $E = mc^2$, and think bubbles saying 'I've got it' or 'A-ah! So that's how it is'.

In the years since Chambers' original work, students' drawings have changed very little,[11] with research indicating that the stereotype begins to emerge at about grade 2 and is well-established and held by the majority of students by grade 5.

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[11] Barman (1997, 1999), Farland-Smith (2009a), Finson (2002), Fort and Varney (1989), Fralick et al. (2009), Fung (2002), Huber and Burton (1995), Jackson (1992), Losh et al. (2008), Mason et al. (1991), Matthews (1994a, 1996), Newton and Newton (1992, 1998), Rahm and Charbonneau (1997), Rosenthal (1993), She (1995, 1998), and Symington and Spurling (1990)

Not only are these images stable across genders, they seem to be relatively stable across cultural differences,[12] although Song and Kim (1999) suggest that Korean students produce 'slightly less stereotypical' drawings, especially with respect to gender and age, than students in the United States. Generally, they draw younger scientists than their Western student counterparts – drawings that probably reflect the reality of the Korean scientific community. In a study of 358 students in grades 1–7 in Southwest Louisiana, Sumrall (1995) found that African American students (especially girls) produced less stereotyped drawings than Euro-Americans with respect to both gender and race. Interestingly, the drawings of African American boys showed an equal division of scientists by race but an 84% bias in favour of male scientists. Many researchers have pointed out that girls are generally less stereotyped in their views about science and scientists than are boys. However, Tsai and Liu (2005) note that female Taiwanese students are less receptive than male students to the idea that scientific knowledge is created and tentative rather than discovered and certain. There are some encouraging indications that students, and especially male students in the age range 9–12, produce drawings with fewer stereotypical features following the implementation of gender-inclusive curriculum experiences (Huber and Burton 1995; Losh et al. 2008; Mason et al. 1991).

Of course, there is a strong possibility that researchers can be seriously misled by the drawings students produce. As Newton and Newton (1998) point out, 'their drawings reflect their stage of development and some attributes may have no particular significance for a child but may be given undue significance by an adult interpreting them' (p. 1138). Even though young children invariably draw scientists as bald men with smiling faces, regardless of the specific context in which the scientist is placed, it would be unwise to assume that children view scientists as especially likely to be bald and contented. As Claxton (1990) reminds us, children compartmentalize their knowledge and so may have at least three different versions of the scientist at their disposal: the everyday comic book version, the 'official' or approved version for use in school and their personal (and perhaps private) view. It is not always clear which version DAST is accessing or how seriously the drawer took the task. Simply asking students to 'draw a scientist' might send them a message that a 'typical scientist' exists (Boylan et al. 1992). There is also the possibility that students in upper secondary school or university use their drawings to make a sociopolitical point – for example, that there are too few women or members of ethnic minority groups engaged in science.

Scherz and Oren (2006) argue that asking students to draw the scientist's workplace can be helpful, while Rennie and Jarvis (1995) suggest that students should be encouraged to annotate their drawings in order to clarify meaning and intention. Further insight into students' views can be gained by talking to them about their drawings and the thinking behind them, asking them if they know anyone who uses science in their work (and what this entails), or presenting them with writing tasks based on scientific discovery. Miller (1992, 1993) advocates the

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[12] Chambers (1983), Farland-Smith (2009b), Finson (2002), Fung (2002), Laubach et al. (2012), Parsons (1997), She (1995, 1998), and Walls (2012)

following approach: 'Please tell me, in your own words, what does it mean to study something scientifically?' When given the opportunity to discuss their drawings and stories with the teacher, even very young children will provide detailed explanations and rationales (Sharkawy 2006; Sumrall 1995; Tucker-Raymond and colleagues 2007). Interestingly, it is increasingly evident that young children's responses to open-ended writing tasks involving science, scientists and engineers are not stable and consistent: accounts and stories of science produced in science lessons are very different from those produced in language arts lessons (Hodson 1993). Students may even provide significantly different oral and written responses to nature of science questions (Roth and Roychoudhury 1994).

While less restrictive, instruments designed for more flexible and open-ended responses, such as the *Images of Science Probe* (Driver et al. 1996), concept mapping, small group discussion and situated-inquiry interviews (Ryder et al. 1999; Welzel and Roth 1998), sometimes pose major problems of interpretation for the researcher. So, too, do observation studies, unless supported by an interview-based follow-up capable of exploring the impact of context on student understanding. While interviews hold out the possibility of accessing underlying beliefs, their effectiveness can be severely compromised by the asymmetric power relationship between interviewer and interviewee, regardless of whether the interviewer is the teacher or an independent researcher. In an interview situation, some students may be shy or reluctant to talk; they may feel anxious or afraid; they may respond in ways that they perceive to be acceptable to the interviewer, or expected by them. Observation via audio or video recording of group-based tasks involving reading, writing and talking, practical work, role play, debating and drama constitute a less threatening situation for students, though even here there can be problems. Indeed, any classroom activity can be impacted by complex and sometimes unpredictable social factors. These complicating factors can mask or distort the NOS understanding we hope to infer from conversations and actions. In short, all approaches to ascertaining NOS views carry a risk that the characterization or description of science ascribed to the research subject is, in some measure, an artefact of the research method.

28.9 Problems Relating to Authenticity and Context

The context in which an interview question, questionnaire item or assessment task is set and, indeed, whether there is a specific context at all can have a major impact on an individual's response. Decontextualized questions (such as 'What is your view of a scientific theory?' or 'What is an experiment?') can seem infuriatingly vague to students and can be met with seeming incomprehension. Use of such questions can pose major problems of interpretation for the researcher. Conversely, context-embedded questions have domain-specific knowledge requirements that may sometimes preclude students from formulating a response that properly reflects their NOS views. Moreover, respondents may feel constrained by restriction of the question to one context and, in consequence, unable to communicate what they know about the many significant differences in the ways that scientists in different fields conduct investigations. Familiarity with the context, understanding of the underlying science concepts, interest in the situation and opportunity to utilize knowledge about other situations are all crucial to ensuring that we access students' authentic NOS understanding. Put simply, questions set in one context may trigger different responses from essentially the same questions set in a different context (Leach and colleagues 2000) – a finding that is especially significant in research that addresses NOS views in the context of scientific controversies (Smith and Wenk 2006) and socioscientific issues (Sadler and Zeidler 2004). It should also be noted that further important perspectives and issues relating to assessment are raised by recent curricular interest in scientific argumentation[13] and modelling,[14] though constraints on space preclude discussion here.

It would be surprising if students didn't have different views about the way science is conducted in school and the way science is conducted in specialist research establishments. Hogan (2000) refers to these different views as students' *proximal* knowledge of NOS (personal understanding and beliefs about their own science learning and the scientific knowledge they encounter and develop in science lessons) and *distal* knowledge of NOS (views they hold about the products, practices, codes of behaviour, standards and modes of communication of professional scientists). Sandoval (2005) draws a similar distinction between students' *practical* and *formal* epistemologies. Contextualized questions that ask students to reflect on their own laboratory experiences are likely to elicit the former, questions of a more general, de-contextualized nature ('What is science?' or 'How do scientists validate knowledge claims?') are likely to elicit the latter. The problem for the researcher is to gauge the extent to which these differences exist and how they are accessed by different research probes. The problem for the teacher is to ensure that students are aware of the crucial distinctions as well as the similarities between science in school and science in the world outside school. It may also be the case that students hold significantly different views of science as they perceive it to be and science as they believe it *should* be – a distinction that Rowell and Cawthron (1982) and Chen (2006) were able to accommodate in their research.

A further complication to ascertaining students' NOS views is the significant potential for mismatch between what individuals say about their NOS understanding and what they do in terms of acting on that understanding. Thus, the question arises: Should we seek to ascertain *espoused* views or views *implicit in actions?*

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[13] Important literature sources include Duschl (2008), Erduran (2008), Erduran et al. (2004), Kelly and Takao (2002), Naylor et al. (2007), Osborne et al. (2004), Sampson and Clark (2006, 2008), Sandoval and Millwood (2005), Shwarz et al. (2003), Takao and Kelly (2003), and Zeidler et al. (2003).

[14] Suitable references include Acher et al. (2007), Chittleborough et al. (2005), Coll (2006), Coll and Treagust (2003a), Duschl et al. (2007), Hart (2008a), Henze et al. (2007a, b), Justi and Gilbert (2002a), Justi and van Driel (2005), Kawasaki et al. (2004), Lehrer and Schauble (2000), Lin and Chiu (2007), Maia and Justi (2009), Perkins and Grotzer (2005), Prins et al. (2008), Raghavan et al. (1998a, b), Saari and Viiri (2003), Schauble (2008), Smith et al. (2000), Taylor et al. (2003), Treagust et al. (2002, 2004), van Driel and Verloop (1999), and Webb (1994).

The former would probably be best served by questionnaires, writing tasks and interviews; the latter would require inferences to be drawn from observed behaviours and actions – for example, responding to scientific texts, searching the Internet and formulating reports of investigations. The crucial distinction between *teachers'* NOS views implicit in action and those supposedly revealed by pencil-and-paper tests is explored at length by Guerra-Ramos (2012). Of particular value for use with teachers and student teachers is Nott and Wellington's (1996, 1998, 2000) 'Critical Incidents' approach. In group settings, or in one-on-one interviews, teachers (or student teachers) are invited to respond to descriptions of classroom events, many related to hands-on work in the laboratory, by answering three questions: What would you do? What could you do? What should you do? Responses, and the discussion that ensues, may indicate something about the teachers' views of science and scientific inquiry and, more importantly perhaps, how this understanding is deployed in classroom decision-making. Similar approaches using video and multimedia materials have been used by Bencze and colleagues (2009a), Hewitt and colleagues (2003), Wong and colleagues (2006) and Yung and colleagues (2007).[15]

Even if we solve all these problems, we are still confronted with decisions about how to interpret and report the data. Should we adopt a *nomothetic* approach that focuses on the extent to which the students' or teachers' views match a prespecified 'ideal' or approved view? Attempts to distinguish 'adequate' NOS views from 'inadequate' views involve judgement about the rival merits of inductivism and falsificationism, Kuhnian views versus Popperian views, realism versus instrumentalism, and so on. None of these judgements is easy to make and may even be counterproductive to good NOS learning. Does it make more sense, then, to opt for an *ideographic* approach? Should we be satisfied to describe the views expressed by students and seek to understand them 'on their own terms'?

A major complicating factor is that students will not necessarily have coherent and consistent views across the range of issues embedded in the notion of NOS. Rather, their views may show the influence of several different and possibly mutually incompatible philosophical positions. As Abd-El-Khalick (2004) points out, what researchers see as inconsistencies in the NOS views of students at the undergraduate and graduate levels may be seen by the students as 'a collection of ideas that make sense within a set of varied and personalized images of science' (p. 418). Moreover, older students, with more sophisticated NOS understanding, will have recognized that inquiry methods vary between science disciplines and that the nature of knowledge statements varies substantially with content, context and purpose. Few research instruments are sensitive to such matters. By assigning total scores rather than generating a profile of views, the research conflates valuable data that could inform the design of curriculum interventions.

Rather than assigning individuals to one of several predetermined philosophical positions, it might make more sense to refer to their *Personal Framework of NOS*

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[15] Other important studies of video-based teacher professional development programmes include Borko and colleagues (2008), Rosaen and colleagues (2008), Santagata and colleagues (2007) and Zhang and colleagues (2011).

Understanding and seek to highlight its interesting and significant features, an undertaking that could be facilitated by the use of repertory grids (as in the study by Shapiro 1996).[16] One such recent study by Ibrahim et al. (2009) seeks to consolidate data from a purpose-built questionnaire into NOS profiles. The questionnaire, *Views about Scientific Measurement* (VASM), which comprises six items addressing aspects of NOS and eight items dealing with scientific measurement, uses a common context (in earth sciences) and allows space for students to elaborate on their response or compose an alternative. The data, obtained from 179 science undergraduates, were found to cluster into four partially overlapping profiles, which the authors refer to as *modellers*, *experimenters*, *examiners* and *discoverers*. For *modellers*, theories are simple ways of explaining the often complex behaviour of nature; they are constructed by scientists and tested, validated and revised through experimentation. Creativity plays an important role in constructing hypotheses and theories and in experimentation. When there are discrepancies between theoretical and experimental results, both theory and the experimental data need to be scrutinized. *Experimenters* also believe that scientists should use experimental evidence to test hypotheses and theories but should do so in accordance with a strict scientific method. In situations of conflict, data have precedence over theories. *Examiners* regard the laws of nature as fixed and 'out there' waiting to be discovered through observation, rather than constructed by scientists. Experimental work is essential; it is not informed by theory. Scientists may use both the scientific method and their imagination, but experimental data always have precedence over theories. *Discoverers* also believe that the laws of nature are out there waiting to be discovered through observation. Only experiments using the scientific method can be used to generate laws and theories. If experimental data conflict with a previously established theory, then both the theory and the data need to be checked.[17] Profiling could solve many of the problems associated with the compilation and interpretation of data on NOS understanding among both students and teachers.

28.10 Some Current Emphases in NOS-Oriented Curricula

Despite the many caveats concerning the validity and reliability of research methods, it is incumbent on teachers, teacher educators and curriculum developers to pay attention to the rapidly growing number of studies indicating that both students and

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[16] Repertory grids enable researchers to ascertain links between different facets of an individual's knowledge and understanding (and between understanding and actions) in quantitative form (Fransella and Bannister 1977). Using them over the lifetime of a research project enables a developmental record of students' (or teachers') views to be built up. Because repertory grids often produce surprising data and highlight inconsistencies in respondents' views, they provide a fruitful avenue for discussion and exploration of ideas. For these reasons, Pope and Denicolo (1993) urge researchers to use them as 'a procedure that facilitates a conversation' (p. 530).

[17] Interestingly, as a percentage of the total, the modeller profile was more common among students following a 4-year science foundation course than among physics majors.

teachers have inadequate, incomplete or confused NOS understanding.[18] Two points are worth making. First, the goal of improving NOS understanding is often prejudiced by stereotyped images of science and scientists consciously or unconsciously built into school science curricula[19] and perpetuated by science textbooks.[20] This should be a relatively easy problem to fix, and it is fair to say that the situation is not nearly so dire as it was a decade or so ago. Second, research has shown that, in general, an *explicit* approach is much more effective than an *implicit* approach in fostering more sophisticated conceptions of NOS.[21]

In an explicit approach, NOS understanding is regarded as curriculum content, to be approached carefully and systematically, just like any other lesson content. This does not entail a didactic or teacher-centred approach or the imposition of a particular view through exercise of teacher authority, but it does entail rejection of the belief that NOS understanding will just develop in students as a by-product of engaging in other learning activities. Most effective of all are approaches that have a substantial reflective component.[22] Adúriz-Bravo and Izquierdo-Aymerich (2009), Howe and Rudge (2005) and Rudge and Howe (2009) argue that an explicit reflective approach is particularly effective when historical case studies are used to engage students in the kinds of reasoning used by scientists originally struggling to make sense of phenomena and events and to construct satisfactory explanations, while Wong and colleagues (2008, 2009) have shown the value of embedding explicit teaching of NOS within a consideration of important socioscientific issues.

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[18] Abd-El-Khalick and Lederman (2000a, b), Abell and Smith (1994), Aikenhead and Ryan (1992), Akerson and Buzzelli (2007), Akerson and Hanuscin (2007), Akerson et al. (2008), Barman (1997), Apostolou and Koulaidis (2010), Brickhouse et al. (2002), Carey and Smith (1993), Carey et al. (1989), Chambers (1983), Dagher et al. (2004), Dogan and Abd-El-Khalick (2008), Driver et al. (1996), Duveen et al. (1993), Finson (2002, 2003), Fung (2002), Griffiths and Barman (1995), Hodson (1993), Hofer (2000), Hogan and Maglienti (2001), Honda (1994), Irez (2006), Kang et al. (2005), Koren and Bar (2009), Larochelle and Desautels (1991), Leach et al. (1996, 1997), Lederman (1992, 1999), Liu and Lederman (2002, 2007), Liu and Tsai (2008), Lubben and Millar (1996), Lunn (2002), Mbajiorgu and Iloputaife (2001), Meichtry (1992), Meyling (1997), Moseley and Norris (1999), Moss et al. (2001), Palmer and Marra (2004), Parsons (1997), Paulsen and Wells (1998), Rampal (1992), Rubin et al. (2003), Ryan (1987), Ryan and Aikenhead (1992), Ryder et al. (1999), Sandoval and Morrison (2003), Schommer and Walker (1997), She (1995, 1998), Smith and Wenk (2006), Smith et al. (2000), Solomon et al. (1994), Solomon et al. (1996), Song and Kim (1999), Sumrall (1995), Tucker-Raymond et al. (2007), Tytler and Peterson (2004), Vázquez and Manassero (1999), Vázquez et al. (2006), and Windschitl (2004)

[19] Bell et al. (2003), Hodson (1998), and Milne (1998).

[20] Abd-El-Khalick (2001), Abd-El-Khalick et al. (2008), Knain (2001), Kosso (2009), McComas (1998), van Eijck and Roth (2008), and Vesterinen et al. (2011).

[21] Abd-El-Khalick (2001, 2005), Abd-El-Khalick and Lederman (2000a), Akerson and Abd-El-Khalick (2003, 2005), Akerson and Hanuscin (2007), Bell (2004), Bell et al. (2000, 2011), Faikhamta (2012), Hanuscin et al. (2006, 2011), Khishfe (2008), Khishfe and Abd-El-Khalick (2002), Lederman and Abd-El-Khalick (1998), Lin et al. (2012), Morrison et al. (2009), Posnanski (2010), Ryder (2002), Scharmann et al. (2005), Schwartz and Lederman (2002), and Schwartz et al. (2004).

[22] Akerson and Donnelly (2010), Akerson and Volrich (2006), Akerson et al. (2000, 2010), Heap (2006), and Lucas and Roth (1996).

Other notable research studies include the finding by Schwartz et al. (2004) that preservice teachers' NOS understanding was favourably enhanced when their course included a research component and journal-based assignments; the report by Morrison et al. (2009) that substantial gains in NOS understanding are achieved when explicit, reflective instruction in NOS is augmented by opportunities to interview practising scientists about their work and/or undertake some job sharing; and the study by Abd-El-Khalick and Akerson (2009) that notes major gains in the NOS understanding of preservice elementary teachers when explicit, reflective instruction is supported by use of metacognitive strategies (especially concept mapping), opportunities to research the development of their peers' NOS understanding and the chance to discuss case studies of elementary science classes oriented towards NOS teaching. A further raft of studies point to the key role played by teachers' NOS-oriented pedagogical content knowledge, curriculum awareness, confidence, self-efficacy and access to appropriate curriculum resources (Hanuscin et al. 2011; Lederman et al. 2012; Ryder and Leach 2008). My own views on how we can build and implement a curriculum to achieve enhanced levels of NOS understanding are discussed at length in Hodson (2009).

It is both notable and disappointing that the gains in NOS understanding consequent on exposure to explicit, reflective instruction are considerably less substantial in relation to the sociocultural dimensions of science than for other NOS elements.[23] The drive to equip students with an understanding of science in its social, cultural, economic and political contexts is, of course, the underpinning rationale of the so-called science-technology-society (STS) approach – more recently expanded to STSE (where E stands for environment). STS(E) has always been a purposefully ill-defined field that leaves ample scope for varying interpretations and approaches, and much has changed over the years in terms of its priorities and relative emphases.[24]

Aikenhead (2005, 2006) describes how the early emphasis on values and social responsibility was systematized by utilizing a theoretical framework deriving from sociology of science and encompassing two key aspects of NOS: (i) the social interactions of scientists *within* the scientific community and (ii) the interactions of science and scientists with social aspects, issues and institutions *external* to the community of scientists. In the terms used by Helen Longino (1990), this is a distinction between the *constitutive* values of science (the drive to meet criteria of truth, accuracy, precision, simplicity, predictive capability, breadth of scope and problem-solving capability) and the *contextual* values that impregnate the personal, social and cultural context in which science is organized, supported, financed and conducted. Allchin (1999) draws a similar distinction between the *epistemic* values of science and the *cultural* values that infuse scientific practice. Both emphases

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[23] Akerson et al. (2000), Dass (2005), Lederman et al. (2001), Moss et al. (2001), Tairab (2001), and Zémplen (2009).

[24] Aikenhead (2003, 2005), Barrett and Pedretti (2006), Bennett et al. (2007), Cheek (1992), Fensham (1988), Gallagher (1971), Gaskell (2001), Hurd (1997), Kumar and Chubin (2000), Lee (2010), Nashon et al. (2008), Pedretti (2003), Pedretti and Nazir (2011), Solomon and Aikenhead (1994), and Yager (1996).

have remained strong, though much has changed with respect to the sociopolitical and economic contexts in which educators and scientists work, our understanding of key issues in the history, philosophy and sociology of science and our theoretical knowledge concerning concept acquisition and development.

Drawing on the metaphor deployed by Sauvé (2005) in her analysis of trends in environmental education, Pedretti and Nazir (2011) describe variations and shifts in the focus of STSE in terms of ‘a vast ocean of ideas, principles, and practices that overlap and intermingle one into the other’ (p. 603). The six currents identified are as follows: *application/design* (practical problem solving through designing new technology or adapting old technologies), *historical* (understanding the sociocultural embeddedness of science and technology), *logical reasoning* (using a range of perspectives, including many outside science, to understand scientific and technological developments), *value-centred* (addressing the multidimensionality of socioscientific issues, including moral-ethical concerns), *sociocultural* (recognizing and critiquing science and technology as social institutions) and *socio-ecojustice* (critiquing and addressing socioscientific issues through direct and indirect action). Five of these categories include elements of NOS, as defined above.

Concern with constitutive and contextual values, and the ways in which these values have shifted in recent years, has been the trigger for renewed interest in the changing nature of NOS – in particular, the key differences between contemporary practice at the cutting edge of scientific research and what might be called ‘classical scientific research’ (the focus for much of school science), especially with regard to methods, publication practices, sponsorship and funding. Forty years ago, sociologist Robert Merton (1973) identified four ‘functional norms’ or ‘institutional imperatives’ that govern the practice of science and the behaviour of individual scientists, whether or not they are aware of it. These norms are not explicitly taught; rather, newcomers are socialized into the conventions of scientific practice through the example set by more senior scientists. Merton argued that these norms constitute the most effective and efficient way of generating new scientific knowledge and provide a set of ‘moral imperatives’ that serves to ensure good and proper conduct:

- *Universalism* – science is universal (i.e. its validity is independent of the context in which it is generated or the context in which it is used) because evaluation of knowledge claims in science uses objective, rational and impersonal criteria rather than criteria based on personal, commercial or political interests and is independent of the reputation of the particular scientist or scientists involved.
- *Communality* – science is a cooperative endeavour and the knowledge it generates is publicly owned. Scientists are required to act in the common good, avoid secrecy and publish details of their investigations, methods, findings and conclusions so that all scientists may use and build upon the work of others.
- *Disinterestedness* – science is a search for truth simply for its own sake, free from political or economic motivation or strictures, and with no vested interest in the outcome.
- *Organized scepticism* – all scientific knowledge, together with the methods by which it is produced, is subject to rigorous scrutiny by the community of scientists in conformity with clearly established procedures and criteria.

In the traditional forms of basic or fundamental research, usually located in universities and/or government research institutes, the so-called pure scientists constitute their own audience: they determine the research goals, recognize competence, reward originality and achievement, legitimate their own conduct and discourage attempts at outside interference. In the contemporary world, universities are under increasing public pressure to deliver more obvious value for money and to undertake research that is likely to have practical utility or direct commercial value. There are increasingly loud calls for closer links between academia and industry. In this changed sociopolitical environment, scientists are now required to practice what Ziman (2000) calls *post-academic* science.[25] Because contemporary scientific research is often dependent on expensive technology and complex and wide-ranging infrastructure, it must meet the needs and serve the interests of those sponsors whose funds provide the resources. Research is often multidisciplinary and involves large groups of scientists, sometimes extending across a number of different institutions, working on problems that they have not posed, either individually or as a group. Within these teams, individual scientists may have little or no understanding of the overall thrust of the research, no knowledge of their collaborators at a personal level and no ownership of the scientific knowledge that results. A number of governments and universities have moved to privatize their research establishments, that is, sell institutes or laboratories engaged in potentially commercially lucrative research areas to industry and business interests or turn them into independent companies. In consequence, scientists have lost a substantial measure of autonomy. In many universities, the research agenda no longer includes so-called blue skies research (i.e. fundamental research), as emphasis shifts to *market-oriented research*, *outcome-driven research* and ever-shortening *delivery times*. Many scientists are employed on contracts that prevent them from disclosing all their results. Indeed, there is a marked trend towards patenting, privatization and commodification of knowledge. As Ziman (2000) comments, many scientists have been forced to trade the academic kudos of publication in refereed journals for the material benefit of a job or a share in whatever profit there might be from a patented invention.

Varma's (2000) study of the work of scientists in industry paints a vivid picture of disturbing changes in the way research is conducted: customization of research to achieve marketable outcomes, contract funding and strict budget constraints, flexible but strictly temporary teams of researchers assembled for specific projects and a shift in the criteria for research appraisal from the quality and significance of the science to cost-effectiveness. The vested interests of the military and commercial sponsors of research, particularly tobacco companies, the petroleum industry, the food processing industry, agribusiness institutions and pharmaceutical companies, can often be detected not just in research priorities but also in research design, especially in terms of what and how data are collected, manipulated and presented. More subtly, in what data are *not* collected, what findings are omitted from reports and whose

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[25] While Ziman (2000) refers to contemporary scientific practice as *post-academic science*, Funtowicz and Ravetz (1993) call it *post-normal science,* and Gibbons and colleagues (1994) and Nowotny et al. (2003) use the term *mode 2 science*.

voices are silenced. Commercial interests may influence the way research findings are made public (e.g. press conferences rather than publication in academic journals) and the way in which the impact of adverse data is minimized, marginalized, hidden or ignored – issues explored at length in Hodson (2011).

In summary, science can no longer be regarded as the disinterested search for truth and the free and open exchange of information, as portrayed in many school textbook versions of science. Rather, it is a highly competitive enterprise in which scientists may be driven by self-interest and career building, desire for public recognition, financial inducements provided by business and commerce or the political imperatives of military interests. Some would argue that one of the most disturbing features of contemporary science is the effective privatization of knowledge. Science is increasingly conducted behind closed doors, in the sense that many procedures and findings remain secret or they are protected by patenting, thus removing them from critical scrutiny by the community of scientists. The scope of what can be patented has been progressively and systematically broadened, such that the very notion of public accessibility to the store of contemporary scientific knowledge is under threat (Mirowski and Sent 2008). It seems that the realities of contemporary science are in direct contradiction of three, if not all four, of the functional norms identified by Merton. Communality, disinterestedness and organized scepticism have been replaced by 'the entrepreneurial spirit and economic growth, such that scientific intellectual creativity seems to have become synonymous with commodity' (Carter 2008, p. 626). Our definitions of NOS and the teaching/learning activities we provide in school need to take account of these matters.

28.11 SSI-Oriented Teaching and Its Curriculum Implications

Interestingly, as consideration of the nature of science has become a much more prominent part of regular science curricula, even a central part in many educational jurisdictions, so emphasis in STSE education has shifted much more towards confrontation of socioscientific issues (SSI), what Pedretti and Nazir (2011) call the value-centred current in STSE. Zeidler and colleagues (2005) contrast this orientation with earlier forms of STS or STSE education in terms of its emphasis on developing habits of mind (specifically, developing scepticism, maintaining open-mindedness, acquiring the capacity for critical thinking, recognizing that there are multiple forms of inquiry, accepting ambiguity and searching for data-driven knowledge) and 'empowering students to consider how science-based issues reflect, in part, moral principles and elements of virtue that encompass their own lives, as well as the physical and social world around them' (p. 357). They argue that while STSE education emphasizes the impact of scientific and technological development on society, it does not focus explicitly on the moral-ethical issues embedded in decision-making: 'STS(E) education as currently practiced… only 'points out' ethical dilemmas or controversies, but does not necessarily exploit the inherent pedagogical power of discourse, reasoned argumentation, explicit NOS considerations, emotive, developmental, cultural or epistemological connections within the issues themselves… nor does it consider the moral or character development of students' (p. 359).

Bingle and Gaskell (1994) had earlier noted that STS education tends to emphasize what Bruno Latour (1987) calls 'ready-made science' (with all its attendant implicit messages about certainty) rather than 'science in the making' (with its emphasis on social construction). Simmons and Zeidler (2003) argue that it is the priority given to science in the making through consideration of *controversial* SSI that gives the SSI approach its special character and its unique power to focus on NOS understanding: 'Using controversial socioscientific issues as a foundation for individual consideration and group interaction provides an environment where students can and *will* develop their critical thinking and moral reasoning' (p. 83, emphasis added). In a further attempt at delineation, Zeidler and colleagues (2002) claim that the SSI approach has much broader scope, in that it 'subsumes all that STS has to offer, while also considering the ethical dimensions of science, the moral reasoning of the child, and the emotional development of the student' (p. 344).[26] Robust understanding of NOS is a clear prerequisite for addressing SSI critically and systematically; importantly, enhanced NOS understanding (both *distal* and *proximal*) is also a significant learning outcome of an SSI-oriented approach (Schalk 2012).

If students are to address SSI thoroughly and critically and deal with the NOS issues they raise, they will need the language skills to access knowledge from various sources and the ability to express their knowledge, views, opinions and values in a form appropriate to the audience being addressed. Thus, teachers need to focus students' attention very firmly on the language of science, scientific communication and scientific argumentation and on students' capacity to become critical readers of a wide variety of texts. Because meaning in science is also conveyed through symbols, graphs, diagrams, tables, charts, chemical formulae and equations, 3-D models, mathematical expressions, photographs, computer-generated images, body scans and so on, Lemke (1998) refers to the language of science as 'multimodal communication'. Any one scientific text might contain an array of such modes of communication, such that it may be more appropriate to refer to the *languages* of science:

> Science does not speak of the world in the language of words alone, and in many cases it simply cannot do so. The natural language of science is a synergistic integration of words, diagrams, pictures, graphs, maps, equations, tables, charts, and other forms of visual mathematical expression. (Lemke 1998, p. 3)

Because much of the information needed to address SSI is of the science-in-the-making kind, rather than a well-established science, and may even be located at or near the cutting edge of research, it is unlikely that students will be able to locate it

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[26] See also Eastwood and colleagues (2012), Ekborg and colleagues (2012), Khishfe (2012b), Lee (2012), Lee and Grace (2012), Nielsen (2012b), Robottom (2012), Sadler (2009, 2011), Sadler and Donnelly (2006), Sadler and Zeidler (2005a, b), Sadler and colleagues (2004, 2006, 2007), Schalk (2012), Tytler (2012), Wu and Tsai (2007), Zeidler and Sadler (2008a, b), Zeidler and Schafer (1984), and Zeidler and colleagues (2003, 2005, 2009).

in traditional sources of information like textbooks and reference books. It will need to be accessed from academic journals, magazines, newspapers, TV and radio broadcasts, publications of special interest groups and the Internet, thus raising important issues of *media literacy*. Being media literate means being able to access, comprehend, analyse, evaluate, compare and contrast information from a variety of sources and utilize that information judiciously and appropriately to synthesize one's own detailed summary of the topic or issue under consideration. It means recognizing that the deployment of particular language, symbols, images and sound in a multimedia presentation can each play a part in determining a message's overall impact and will have a profound influence on its perceived value and credibility. It means being able to ascertain the writer's purpose and intent, determine any subtext and implicit meaning and detect bias and vested interest. It means being able to distinguish between good, reliable information and poor, unreliable information. It involves the ability to recognize what Burbules and Callister (2000) call *misinformation*, *malinformation*, *messed-up information* and *useless information*. Students who are media literate understand that those skilled in producing printed, graphic and spoken media use particular vocabulary, grammar, syntax, metaphor and referencing to capture our attention, trigger our emotions, persuade us of a point of view and, on occasions, bypass our critical faculties altogether.

Many SSI are highly controversial, sometimes because the scientific information required to formulate a judgement is incomplete, insufficient, inconclusive or extremely complex and difficult to interpret, sometimes because judgement involves consideration of factors rooted in social, political, economic, cultural, religious, environmental, aesthetic and/or moral-ethical concerns, beliefs, values and feelings. In other words, controversy may be *internal* or *external* to science. Teachers need to make a decision about how they will handle such issues. Should they try to avoid controversy altogether, take a neutral position, adopt the devil's advocate role, try to present a balanced view or advocate a particular position? These questions are discussed at length in Hodson (2011). Further, almost any discussion of a topical SSI is likely to raise questions not only about what we *can* or *could* do but also about what is the *right* decision and what we *ought* to do. Because many SSI have this moral-ethical dimension, teachers will also need to foster students' moral development and develop their capacity to make ethical judgments. Helpful discussion of these matters and strategies that teachers might employ can be found in Fullick and Ratcliffe (1996), Jones et al. (2007, 2010) and Reiss (1999, 2003, 2010).[27]

It is also likely that addressing SSI in class will generate strong feelings and emotions, with students' views and assumptions being strongly influenced by personal experiences and the experiences of friends and family and by socioculturally determined predispositions and worldviews. A student's sense of identity, comprising

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[27] See also Beauchamp and Childress (2008), Clarkeburn (2002), Goldfarb and Pritchard (2000), Keefer (2003), Levinson and Reiss (2003), Sadler and Zeidler (2004), Sáez et al. (2008), and Saunders and Rennie (2013).

ethnicity, gender, social class, family and community relationships, economic status and personal experiences extending over many years, will necessarily impact on their values, priorities and preferences and influence the ways in which they engage in discussion and the conclusions they reach. Teachers introducing SSI into the curriculum need to be sensitive to these influences and will need to assist students in dealing with potentially stressful and disconcerting learning situations. It is here that notions of *emotional intelligence*, *emotional literacy* and *emotional competence* can be helpful.[28] Although these three terms are closely related, Matthews (2005) chooses to draw a distinction between the individualistic nature of emotional intelligence and the strongly social nature of emotional literacy. Thus, he argues emotional intelligence refers to an individual's ability to perceive, describe, appraise and express emotions, understand emotions and emotional knowledge, access and/or generate appropriate feelings when they facilitate thought or manage them productively when they might inhibit, while emotional literacy is the capacity to be receptive to a wide range of feelings, empathize with others and continuously monitor the emotional climate in which one is located. Emotional competence may be seen as an amalgam of the two. In general, the goal of emotional literacy is awareness and management of one's emotions in both joyful and stressful situations, the confidence and self-assurance to understand one's own emotions and the capacity to deal with them in a positive and intentional way. It is closely related to notions of self-awareness, self-image, self-esteem and sense of identity, and less directly with self-efficacy and agency.

28.12 Future Developments

In a chapter dealing with the origin, development, implications and shifting emphases of NOS-oriented curricula, it is perhaps appropriate to speculate on future developments or even to promote one's own ideas for further development. On this latter count, I count myself among those authors who argue that current conceptions of STSE or SSI-oriented science education do not go far enough, among those who advocate a much more radical, politicized form of SSI-oriented teaching and learning in which students not only address complex and often controversial SSI, and formulate their own position concerning them, but also prepare for, and engage in, sociopolitical actions that they believe will 'make a difference', asking critical questions about how research priorities in science are determined, who has access to science, how science could (and perhaps should) be conducted differently, how scientific and technological knowledge are deployed, whose voices are heard and whose reading

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[28] Goleman (1985, 1996, 1998), Matthews et al. (2002), Matthews and colleagues (2004a, b), Saarni (1990, 1999), Salovey and Meyer (1990), Salovey and Shayter (1997), Steiner (1997), Sharp (2001) and Zeidner et al. (2009).

of a situation are considered.[29] It is a curriculum clearly rooted in notions of equity and social justice.

The likelihood of students becoming active citizens in later life is increased substantially by encouraging them to take action *now* (in school), providing opportunities for them to do so and giving examples of successful actions and interventions engaged in by others. Students need knowledge of actions that are likely to have positive impact and knowledge of how to engage in them. A key part of preparing for action involves identifying action possibilities, assessing their feasibility and appropriateness, ascertaining constraints and barriers, resolving any disagreements among those who will be involved, looking closely at the actions taken by others (and the extent to which they have been successful) and establishing priorities in terms of what actions are most urgently needed (and can be undertaken fairly quickly) and what actions are needed in the longer term. It is essential, too, that all actions taken by students are critically evaluated and committed to an action database for use by others. From a teaching perspective, it is important that care is taken to ensure both the appropriateness of a set of actions for the particular students involved and the communities in which the actions will be situated and the overall practicality of the project in terms of time and resources. It is also essential that students gain robust knowledge of the social, legal and political system(s) that prevails in the communities in which they live and develop a clear understanding of how decisions are made within local, regional and national government and within industry, commerce and the military. Without knowledge of where and with whom power of decision-making is located and awareness of the mechanisms by which decisions are reached, effective intervention is not possible. Thus, an issue-based and action-oriented curriculum requires a concurrent programme designed to achieve a measure of *political literacy*, including knowledge of how to engage in collective action with individuals who have different competencies, backgrounds and attitudes, but shares a common interest in a particular SSI. It also includes knowledge of likely sympathizers and potential allies and strategies for encouraging cooperative action and group interventions.

Desirable as this approach may be in meeting the needs of citizens in the early twenty-first century, converting such curriculum rhetoric into practical action in real classrooms is an extraordinarily tall order for teachers to undertake. It is a tall order for three reasons. First, because it radically changes the nature of the school curriculum and puts a whole raft of new demands on teachers. Second, because it challenges many of the assumptions on which schooling is traditionally based. Third, because it is predicated on a commitment to bringing about extensive and wide-ranging social change at local, regional, national and international levels. It will only occur when sufficient teachers, teacher educators, curriculum developers and curriculum policy makers are convinced of the importance, desirability and feasibility of

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[29] See also Alsop (2009), Alsop and colleagues (2009), Bencze and Alsop (2009), Bencze and colleagues (2009b, 2012), Bencze and Sperling (2012), Calabrese Barton and Tan (2009, 2010), Chawla (2002a, b), Hart (2008b, c), Hodson (2003, 2011, 2014), Mueller (2009), Mueller et al. (2013), Roth (2009a, b, 2010), Roth and Désautels (2002, 2004), and Santos (2008).

addressing SSI in the science classroom and encouraging sociopolitical action, and when there is commitment to teach and confidence in doing so through awareness of appropriate pedagogical strategies, capacity to organize the required classroom environment and access to suitable resources. The real breakthrough will come when individual teachers are able to find and work with like-minded colleagues to form pressure groups that can begin to influence key decision-making bodies. However, such matters are well outside the scope of this chapter.

28.13 Final Thoughts

The primary purpose of this chapter has been to convey something of the extraordinary rise and widening scope of curriculum interest in NOS understanding. From very humble beginnings (e.g. 'Let's ensure that we teach about the methods that scientists use as well as paying attention to content'), curriculum interest in NOS has developed into a major influence on science education in many parts of the world. Changing views of what counts as NOS knowledge have led to further extensive developments, including concern with the characteristics of scientific inquiry, the role and status of the scientific knowledge it generates, modelling and the nature of models, how scientists work as a social group, the linguistic conventions for reporting and scrutinizing knowledge claims, the ways in which science impacts and is impacted by the social context in which it is located and the centrality of NOS in addressing the science underpinning SSI. More recently, it has been extended in such a way that some educators see NOS as a central plank in citizenship education. In my view, the next development in the extension of NOS-oriented education is the establishment of an issue-based and action-oriented curriculum capable of directing critical attention to (i) the way contemporary research and development in science and technology is conceived, practised and funded and (ii) the ways in which scientific knowledge is accessed and deployed in establishing policy and priorities with respect to SSI.

A key issue concerns the NOS sophistication we should pursue via the school curriculum. It is unrealistic as well as inappropriate to expect students to become highly skilled philosophers, historians and sociologists of science. Rather, we should select NOS items for the curriculum in relation to important educational goals: the need to motivate students and assist them in developing positive but critical attitudes towards science, the need to pay close attention to the cognitive goals and emotional demand of specific learning contexts, the creation of opportunities for students to experience *doing* science for themselves, the capacity to address complex socioscientific issues with critical understanding, concern for values issues and so on. The degree of sophistication of the NOS items we include should be appropriate to the stage of cognitive and emotional development of the students and compatible with other long- and short-term educational goals. There are numerous goals for science education (and education in general) that can, will and *should* impact on decisions about the NOS content of lessons. Our concern is not just good philosophy of science, good sociology of science or good history of science, not just authenticity and preparation for sociopolitical action, but the educational needs and interests of the students – *all* students. Selection of NOS items should consider the *changing* needs and interests of students at different stages of their science education, as well as take cognizance of the views of 'experts' (philosophers of science, historians of science, sociologists of science, scientists, science educators) and the need to promote the wider goals of (i) authentic representation of science and (ii) pursuit of critical scientific literacy.

It is considerations like these that prompted Michael Matthews (1998) to advocate the pursuit of 'modest goals' concerning HPS in the school science curriculum. In his words, 'there is no need to overwhelm students with cutting edge questions' (p. 169). Perhaps so, but agreement with the notion of modest goals still raises a question of what they should comprise. At the very least, we should include the following: consideration of the relationship between observation and theory; the role and status of scientific explanations (including the processes of theory building and modelling); the nature of scientific inquiry (including experiments, correlational studies, blind and double-blind trials, data mining and all the other notable variations among the subdisciplines of science); the history and development of major ideas in science; the sociocultural embeddedness of science and the interactions among science, technology, society and environment; the distinctive language of science; the ways in which scientific knowledge is validated through criticism, argument and peer review; moral-ethical issues surrounding science and technology; error, bias, vested interest, fraud and the misuse of science for sociopolitical ends; and the relationship between Western science and indigenous knowledge. A number of these elements are present in some science curricula, but more often than not, they are implicit, part of the hidden curriculum, embedded in language, textbook examples, laboratory activities and the like, and so dependent, ultimately, on teachers' nature of science views.

This is a demanding prescription and I readily acknowledge that telling students too early in their science education that scientific inquiry is context dependent and idiosyncratic could be puzzling, frustrating and even off-putting. This is a similar point to Brush's (1974) concern that teaching history of science can have an adverse effect on young students by undermining their confidence in science and scientists. One approach is to take our cue from secondary school chemistry curricula, where we often begin with some very simple representations, such as 'elements are either metals or non-metals' or 'bonding is either covalent or electrovalent'. We then proceed to qualify these assertions in all manner of ways: 'there are varying degrees of metallic/non-metallic character, depending on atomic size and electron configuration' and 'there is a range of intermediate bond types, including polarized covalent bonds and lattices involving highly distorted ions, as well as hydrogen bonding, van der Waal's forces, and so on'. Similarly, in the early years, we may find it useful to characterize scientific inquiry as a fairly standard set of steps. Within this simple representation, we can emphasize the importance of making careful observations (using whatever conceptual frameworks are available and appropriate to the students' current stage of understanding), taking accurate measurements, systematically controlling variables, and so on. As students become more experienced, they can be introduced to variations in approach that are necessary as contexts change – for example, the startlingly different approaches adopted by experimental particle physicists, synthetic organic chemists and evolutionary biologists.

Matthews (2012) makes the same point when he states that students have 'to crawl before they can walk, and walk before they can run. This is no more than commonsensical pedagogical practice' (p. 21). The shift from nature of science (NOS) to features of science (FOS), with its inbuilt recognition of diversity among the sciences and the significant changes in constitutive values from 'classical' scientific research to contemporary, post-Mertonian scientific practice, would be a major step in assisting teachers to pitch their teaching at a level appropriate to the students and to the issues being addressed.

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