Chapter 69
Nature of Science in Science Education: Toward a Coherent Framework for Synergistic Research and Development

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The centrality of nature of science (NOS) to precollege science education cannot be overstated. NOS has been, and continues to be accorded a central position among the few major themes that cut across reform documents in science education around the globe both past (Robinson 1965) and present (Millar and Osborne 1998). Vigorous emphasis on helping learners develop informed understandings of NOS dates back to the 1950s (Wilson 1954). Since then, such emphasis has been accompanied by intensive lines of research that targeted assessing students' and teachers' views of NOS (see Driver et al. 1996; Lederman et al. 1998), developing and investigating curricular materials and pedagogical approaches to help students (see Lederman 1992; Meichtry 1993) and teachers (see Abd-El-Khalick and Lederman 2000) internalize more accurate understandings of NOS, and investigating factors and approaches mediating and facilitating the translation of teachers' understandings of NOS into classroom practice. These research and development efforts, no doubt, resulted in some progress. However, much remains to be done. Recent studies indicate that, around the globe, elementary (Khishfe and Abd-El-Khalick 2002), middle (Kang et al. 2005), high school (Dogan and Abd-El-Khalick 2008), and college students (Ibrahim et al. 2009), as well as teachers (Dogan and Abd-El-Khalick 2008) continue to ascribe to naïve views of NOS. What is more, pre-service and in-service science teachers holding informed views of NOS continue to struggle with integrating and enacting these views in their instructional practice, and consequently with helping their students achieve the desired understandings of NOS (Abd-El-Khalick and Akerson 2004). Progress to date remains frustratingly mismatched with the longevity and intensity of the

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B.J. Fraser et al. (eds.), *Second International Handbook of Science Education*,
Springer International Handbooks of Education 24, DOI 10.1007/978-1-4020-9041-7_69,

research and development efforts dedicated to teaching and learning about NOS in science education.

Obviously, a host of factors underlies the current state of affairs. These include the well-documented complexities associated with bringing about significant and systemic change to the beliefs and practices inherent to science teaching and learning, science teacher education, schools and schooling, and educational systems and processes. Making headway with an especially challenging domain, such as teaching and learning about NOS, necessitates synergistic, long-term research and development efforts. While these efforts should be pluralistic rather than single-minded, they nonetheless need to draw on a coherent broad framework. Such a framework makes discourse, discord, and collaboration among researchers possible and allows them to dissect, critique, and build on each others' work rather than talk and work past each other. I believe that such a framework has been, and continues to be, wanting because of a lack of clarity about the nature of the construct of NOS. In particular, I believe that discourse, research, and development related to NOS in science education have been guided by two broad, mostly confounded, perspectives which I label here as the "lived" and "reflective" perspectives on NOS. The result has been bifurcated research and development efforts that, at best, lack synergy and, at worst, seriously hamper progress within the field.

The present chapter aims to explicate the assumptions underlying the two perspectives, and examine their implications for research and development efforts related to teaching and learning about, as well as assessing conceptions of, NOS. In so doing, the chapter takes a significant step toward outlining a framework that could foster synergy within the field and help advance both research and development efforts related to NOS in science education.

First Things First: What Science? And Whose NOS?

The lived and reflective perspectives are not related to the often invoked questions about "What science?" (cf. Cobern and Loving 2000), that is, claims about what counts as science from multicultural perspectives in contrast to more universalist conceptions of the scientific endeavor. Nor are the two perspectives related to questions about "Whose NOS?" (cf. Alters 1997), that is, the often invoked discords about NOS derived from philosophical, historical, and sociological studies of science. Instead, the lived and reflective perspectives derive from our conceptualization as a community of the nature of the construct of NOS. However, before proceeding to examine the two perspectives, I address the questions of what science and whose NOS because answers to these questions are crucial components to any framework that aims to guide research and development on NOS in science education.

The What Science Question: A Gentle Reminder About Our Charge and Mission

A concern that is often raised in relation to conceptualizing NOS derives from the question of what science serves as the frame of reference. The question generally leads to discussions about Western or universal science versus multicultural science or indigenous knowledge, and associated arguments as to the hegemony of the former and the need to address the latter in science education (Atwater 1993), including making provisions for multicultural science or indigenous knowledge in the science curriculum. Cobern and Loving (2000, p. 50) conducted a comprehensive and fair-minded analysis of this question and concluded that:

> Although one may hate to use the word hegemony, Western science would co-opt and dominate indigenous knowledge if it were incorporated as science. Therefore, indigenous knowledge is better off as a different kind of knowledge that can be valued for its own merits.

Irrespective of the merits of arguments for or against multicultural science or indigenous knowledge, the mission and charge of science educators do not include deciding what is and is not science, even though they need to be profoundly and critically cognizant of the bases that underlie such decisions. In this era of big science (Nye 1996), the academy, scientific community, and scientific establishment largely determine what counts and does not count as science. Such determination takes several forms ranging from explicit position statements, such as the position in the United States of the National Academy of Science (1998) on creation science, to endorsements in the form of providing or withholding funding (e.g., through the National Science Foundation in the United States and similar establishments in other nations), to the creation of new disciplinary positions and departments at research universities.

I believe that the charge for the science education community is to educate all learners and the general public about science that is sanctioned by the academy and the establishment. The functional term here being to educate, as compared to indoctrinate. Education entails helping all learners and citizens develop the understandings, skills, attitudes, and habits of mind–with special attention to the development of a critical stance toward, and healthy skepticism about, science itself–that would allow them to make sense of and utilize science to lead more fulfilling lives, make informed decisions about science-related personal and social issues, pursue a host of science-related careers, and meaningfully participate in cultural discourse championing or disputing science. In this regard, if science educators decide to make the question of what science their primary business, they might find themselves going down some slippery slopes (Loving 1997). For example, it could be argued that creation science is one form of indigenous knowledge endorsed by a group of individuals who are both alienated and marginalized by Western science. Thus, the argument would continue, creation science deserves a place in the science curriculum at par with other indigenous sciences!

It cannot be overemphasized that the present argument does not entail that the notion and implications of multicultural science or indigenous knowledge and related research efforts are insignificant or irrelevant to science education. On the contrary, as long as care is taken to not conflate issues of curriculum with ones related to pedagogy, such research would contribute tremendously to science education. For instance, research on indigenous knowledge could inform the development of pedagogical approaches and instructional materials that would empower students to successfully cross the borders between their cultures and the culture of science (cf. Aikenhead and Jegede 1999), make the transition between their life-worlds and that of school science (cf. Costa 1995), or even negotiate the assumptions underlying their worldviews and a scientifically compatible worldview (cf. Cobern 1996). What should be avoided are work and lines of argument that entail the provision of equal time to universal science and indigenous knowledge in the school science curriculum.

The Whose NOS Question: Beyond Pragmatic Irrelevance for Precollege Science Education

Some researchers argue that NOS remains a largely contested area, so much so that discourse, research, and development related to NOS in science education are not altogether plausible (Alters 1997). To be sure, philosophers, historians, and sociologists of science continue to disagree on a number of important aspects of NOS. Such disagreements include, for example, the continuing debates between empiricists (e.g., Van Fraassen 1998) and realists (e.g., Musgrave 1998) as to the ontological status of scientific theories and the entities they often postulate. To be sure, these disagreements about the content of NOS are relevant and need to be meaningfully addressed in any framework that aims to guide synergistic research and development efforts. In essence, what is at issue here is the question of benchmarking views of NOS; that is, deciding what counts as accurate or informed, and what counts as inaccurate or naïve views of NOS. It could be seen that this issue has serious implications for assessing learners' views of NOS, as well as the development of curricula and instructional materials designed to help learners internalize informed or accurate NOS understandings as stipulated in science education reform documents (e.g., American Association for the Advancement of Science [AAAS] 1990).

Two approaches have been used to address the question of benchmarking views of NOS. The first is more negative in its content and implications: It leverages disagreements among philosophers, historians, and sociologists of science as a basis for the implausibility of any benchmarking (e.g., Alters 1997) and, consequently, for questioning the meaningfulness of the notion of teaching and learning about NOS. This approach was heavily criticized for exaggerating disagreements while simultaneously disregarding substantial agreement with regard to some central NOS issues (Smith et al. 1997). The second approach adopted the opposite position, that is, highlighting agreements among philosophers, historians, and sociologists while downplaying, or remaining silent on, continuing controversies. The latter approach is more positive in its content and implications. Indeed, this approach underlies the very development of statements on NOS adopted by reform documents in science education. This approach is most evident in documents, such as *Science for All Americans* (AAAS 1990), where, for example, the aforementioned debates between realists and empiricists were completely disregarded. In other instances, contentious issues were addressed by adopting compromise positions, such as affirming that scientific knowledge is tentative but durable (AAAS 1990, pp. 2–3), which seemingly is an attempt to veer away from realist perspectives on the status of scientific knowledge while simultaneously acknowledging that successes in science cannot simply be explained by social constructivist conceptions of NOS (Brown 1998).

The second approach, which has proven fruitful for guiding a host of research and development efforts, relies on arguments that are pragmatic in nature. One such argument, which we put forth about a decade ago (Abd-El-Khalick et al. 1998), goes something like this: Disagreement on specific conceptualizations of NOS should not be surprising given the multifaceted and complex nature of the scientific enterprise. Also, similar to scientific knowledge, conceptions of NOS are tentative and dynamic: they have changed (and continue to change) throughout the development of science and systematic thinking about its nature and workings (Abd-El-Khalick and Lederman 2000). Nonetheless, at one point in time and at a certain level of generality, there is a shared wisdom (even though no complete agreement) about NOS amongst philosophers, historians, and sociologists of science. For example, presently it is very difficult to reject the theory-laden nature of observation and investigation, or to defend a deterministic or absolute conception of NOS. In other words, a set of generalized, virtually non-controversial notions about NOS, which are relevant to the education of precollege students, could be identified and fruitfully guide research and development efforts in science education (e.g., Abd-El-Khalick et al. 1998). Such NOS aspects have been advanced in recent reform documents (e.g., AAAS 1990) and include, among other dimensions, that scientific knowledge is tentative (subject to change), empirical (based on and/or derived from observations of the natural world), theory-laden (impacted by scientists' theoretical positions and personal histories), creative (partially based on human inference, imagination, and creativity), and social (produced through collaborative and negotiated processes).

The crucial point to emphasize here is that, from a pragmatic perspective, even with these seemingly non-controversial aspects of NOS, much remains to be desired in precollege science classrooms. Students and teachers still ascribe to naïve views of many aspects of NOS, such as a complete lack of appreciation for the social nature of the production and validation of scientific knowledge. Also, teachers continue to structure science instruction in ways, and science textbooks continue to convey images about science, that misrepresent NOS and explicitly communicate myths about its nature and workings. For instance, despite consensus on the theory-laden nature of observation and investigation (Gillies 1998), a large majority of students and science teachers continue to ascribe to naïve inductivist views of NOS. Many science teachers continue to engage their students in activities in which theory-free data are collected and supposedly analyzed. The same teachers continue to be disappointed and frustrated when students fail to discern the obvious patterns in these data that they want students to see, or draw the 'obvious' conclusions that the teachers want students to reach! Similarly, despite it being debunked by philosophers, historians, sociologists, and scientists alike (Bauer 1994), the myth of a universal, step-wise, prescriptive, Scientific Method continues to linger on in some form or another in science textbooks and laboratory manuals (Abd-El-Khalick et al. 2008), and to be posted in prominent places on the walls of science classrooms. Students and teachers continue to believe that scientific knowledge is actually generated and validated through the use of the Scientific Method. Many teachers continue to have students memorize the steps of this so-called method and force students to structure their thinking and activities in science along the rigid lines of this archaic notion.

Similarly, the nature and functions of scientific theories continue to be misconstrued by students and misrepresented by science teachers with discourse that is centered on proving and disproving theories rather than on issues of explanatory and predictive power, generative research potential, and internal consistency. The potentially undesirable consequences of these naïve ideas in propagating and deepening confusion about central issues, such as evolutionary theory versus creation science, are too well known to be reiterated here. What is more, despite the well-established and documented claims as to the centrality of critical social discourse to the generation and validation of scientific knowledge (Longino 1990), students continue to believe that scientists work in isolation and communicate finished products to their colleagues. By the same token, many science teachers continue to deprive students from opportunities to communicate, defend, negotiate, and restructure the ideas they generate in the context of science-based activities. Thus, it could be seen that our work is cut for us even after deciding to forgo—for pragmatic reasons—high-level philosophical, historical, and sociological controversies and limit ourselves to a rather small set of seemingly non-controversial notions about NOS of the sort endorsed in current science education reform documents.

Arguments based on the pragmatic irrelevance of high-level controversies about NOS to precollege science education are plausible and needed in an applied field like science education where teachers around the globe walk into science classrooms every day and convey images, mostly naïve ones, about NOS to their students. However, philosophical, historical, and sociological controversies cannot be dismissed altogether because, in essence, they represent the very content of the construct of NOS. I am afraid that the pragmatic underpinnings of the treatment of NOS in reform documents is either not understood or disregarded more often than not. The various aspects of NOS identified in such documents (e.g., AAAS 1990) or by researchers (e.g., Osborne et al. 2003) sometimes seem to be uncritically accepted as true of NOS. However, in the same way that it is inaccurate and intellectually dishonest to teach students, for example, that scientific knowledge is certain or that scientists are necessarily objective, it is equally problematic to convey the notions that scientific entities are merely social constructions or that scientists' theoretical biases always prevail in the face of evidence (e.g., Khishfe 2008; Pomeroy 1993). Philosophical and historical controversies convincingly show that the latter claims are, at least, contested. The fact of the matter is that seemingly simple aspects, such as the tentative or empirical NOS, are much more complex than is often construed by some researchers and educators engaged with this domain.

There is need to extend the current framework for benchmarking NOS, which focuses on some generalized NOS aspects and is made possible by highlighting philosophical, historical, and sociological agreements while dismissing discords. We need an alternative framework that remains faithful to the controversial nature of some NOS dimensions. At the same time we need to be careful to avoid the perils of dismissing the whole enterprise of NOS because of the noted controversies. We should not lose sight of the fact that science continues to be explicitly and gravely misrepresented in curricular materials and instructional practices. For example, we need to be aware that science textbooks are populated with a host of explicitly stated and didactically taught falsehoods about NOS, such as that, "A scientific law is simply a fact of nature that is observed so often that it becomes accepted as truth. The sun rises in the east each morning is a law of nature because people see that it is true every day" (Phillips et al. 1997, p. 59). This latter statement, it could be seen, presents a bundle of inaccuracies ranging from affirming the inductivist doctrine, to confusing scientific laws with empirical observations, to confirming the absolute nature of scientific knowledge, not to mention giving an outright false example of a scientific law. These are the images of NOS that we need to keep in mind when approaching curricular decisions about the inclusion of more accurate representations of science. Finally, we need to remain keenly mindful of the interests and abilities of our major audience, namely, precollege students.

One viable alternative would be to continue to focus on a set of NOS aspects that currently are emphasized in reform documents and enjoy wide support within the science education community (tentative, empirical, inferential, creative, theory-laden, and social NOS, etc.). These aspects, however, would be addressed at increasing levels of depth as learners move along the educational ladder from elementary school to college-level science teacher education programs. Thus, treatment of the target NOS aspects would span a continuum from general, simple, and unproblematic in elementary grades to specific, complex, and problematized (or controversial) in science teacher education settings, while taking learners' developmental levels into consideration. Additionally, the interrelatedness of these NOS aspects would be progressively examined with greater depth to provide learners with ample opportunities to construct, re-construct, and consolidate their own internally consistent frameworks about the epistemological foundations of science. Table 69.1 provides examples of addressing some NOS aspects under the proposed framework. It could be seen that the level of generality at which NOS aspects are addressed at one end of the continuum (i.e., the elementary level) render them non-controversial, but significantly more accurate than currently propagated myths about NOS. At the secondary level, learners would be expected to discuss aspects of NOS with reasonable levels of sophistication that go beyond superficial platitudes, such as that scientific

Table 69.1 Examples of addressing some aspects of NOS at progressive levels of depth along the educational ladder

Educational level	Examples of target NOS aspects: Tentative NOS	Theory-laden NOS	Empirical NOS	Social NOS	Level of depth
Teacher education	There are debates as to whether scientific knowledge grows by accretion (commensurable across theoretical frames) or through paradigmatic shifts (incommensurable across theoretical frames)	There are debates as to the nature and significance of the theory-ladenness of observation. Is theory ladenness significant beyond situations where the evidence lays at the very edge of the human perceptual apparatus and/or observational instruments?	Scientific theories are underdetermined by evidence. Debates continue about the extent to which rationality versus value judgment mediate the use of evidence in the process of theory choice in science	Debates continue about the viability of social constructionist conceptions in accounting for science's success in the absence of "realist" conceptions. Only "miracle" can explain such success if science was not getting closer to the "true" nature of phenomena!	Specific, complex, problematized (controversial)
Secondary school	Scientific knowledge is expanded, revised, or rejected because of two fundamental reasons: (1) New evidence is brought to bear [Empirical NOS], and/or (2) existing evidence is reinterpreted in light of theoretical advances [Theory-laden NOS]	Theories might determine what scientists "see" when conducting investigations through selective attention and/or influencing the interpretation of "raw" inputs from the environment.	The relationship between scientific knowledge and evidence is indirect. Theories can only be tested by comparing their consequences with empirical observations. Hypotheses do not "jump out" from evidence: Inference beyond the evidence is usually involved [Creative NOS] The relationship between knowledge claims and evidence is mediated by theory [Theory-laden NOS].	The social character of science contributes to its objectivity: Inter-subjective critical discourse through established value-driven channels (e.g., double-blind review procedures) minimizes the subjectivities of participant scientists.	

	Scientific knowledge changes in, at least, two fundamental ways: (1) It is expanded through accretion, and/or (2) discarded and altogether replaced with new knowledge.	Theories are crucial to conducting scientific investigations because theories enable scientists both to choose what evidence to collect (and what evidence to disregard) and how to interpret the collected evidence.		Science is conducted within the context of social institutions and has established and identifiable norms.	⇓
Elementary school	Scientific knowledge is subject to change over time	Scientific investigations always involve theories and empirical observations	Science demands evidence: Scientific knowledge is derived from and/or supported by observations of the natural world	Different groups of scientists contribute to the development of scientific knowledge	General, simple, unproblematic

Note. The treatment of these few NOS elements across the educational ladder is meant to be illustrative rather than exhaustive.

knowledge is tentative. On the other end of the continuum, it could be seen that science teachers would be tackling nuanced complexities about aspects of NOS, including the examination of current controversies among philosophers, historians, and sociologists of science. As a result, science teachers would be better positioned to not only support their students' learning about NOS, but to tailor the level of depth at which NOS is addressed to the specific interests and abilities of those students. Such an approach, it should be noted, is essentially not different from the way science content is currently addressed in various curricula. Consider, for example, the atomic structure and the progression of representations to which students are exposed: from a solar system model of the atom in elementary grades to probability distributions of electron clouds in undergraduate college studies. I believe that the proposed framework both addresses our pragmatic mission as science educators and remains faithful to the status of our knowledge about NOS. Obviously, working out the details of addressing various NOS aspects across the suggested continuum requires further work and research, especially in terms of understanding the developmental appropriateness of the various (often abstract and complex) NOS ideas.

Lived and Reflective Perspectives: Situating NOS

The lived and reflective perspectives are not related to the what science and whose NOS questions. Indeed, I believe advocates of both perspectives are in agreement about the aforementioned answers to these two questions. Differences between the two perspectives are subtle but have significant curricular and pedagogical implications for influencing and assessing learner conceptions of NOS. Advocates of the lived perspective (e.g., Kelly and Duschl 2002) assume that NOS is science or doing science. Thus, NOS is the practice of science. By comparison, advocates of the reflective perspective (e.g., Abd-El-Khalick and Lederman 2000) argue that NOS derives from reflecting on science, it is about the practice of science. The two perspectives lead to different ways of thinking and talking about NOS both among and between science education researchers and science teachers. Some examples might help to clarify the distinction. For instance, it took me a long time to realize that when discussing the so-called Scientific Method with colleagues and science teachers, we sometimes were actually talking past each other because we had different frames of reference in mind, namely, epistemology of science and practice of science. When I say, "There is no such thing as a universal Scientific Method," I am basically arguing that there is no guaranteed method (inductive, deductive, falsificationist, hypothetico-deductive, etc.) that would unerringly lead scientists to the development of valid claims about natural phenomena. When science teachers object to my claim—as they often do—they are usually saying that scientists actually practice the Scientific Method because they do experiments or conduct a set of activities in some set order or another (e.g., observing, making hypotheses, collecting and analyzing data, drawing conclusions, and communicating results). Also, when teachers agree with my claim about the myth of the Scientific Method, they are usually saying that scientists do not necessarily do their activities in a certain sequence but could start at different points and go back and forth among the various steps. Similarly, it took me a while to realize that when some science educators say they have addressed NOS instructionally in some intervention, they simply are referring to the fact that learners were engaged with doing inquiry-based science activities (e.g., McComas 1993).

While the lived and reflective perspectives are necessarily interrelated, they are not identical. At a more basic level, the distinction between the two perspectives is akin to the common conflation of the processes of science and inquiry skills with NOS. For example, the act of observing is a fundamental scientific process: Students and scientists develop varying levels of skill and proficiency in making observations and using various observational instruments. The notion of the theory-laden nature of observation, nonetheless, belongs to the domain of NOS. More importantly, engaging in observation does not necessarily lead the observer to discern or construct the notion of the theory-ladenness of observation. By the same token, students in a physics course can develop crucial inquiry skills, such as controlling variables, and designing and conducting experiments. Engaging these activities, however, does not entail that students would come to understand, for instance, the impossibility of having a crucial experiment in physics, that is, an experiment that conclusively adjudicates between two competing theories that purport to explain the same phenomenon (Duhem 1904–1905/1954). This latter notion belongs to the domain of reflecting on the activities of science, that is, the domain of NOS. Empirical evidence supports these conclusions (e.g., Schwartz et al. 2004). In this regard, a useful heuristic for distinguishing between (the necessarily interrelated) scientific inquiry and NOS is to think of the former as the set of actions undertaken to address foundational issues about theory of scientific method brought about by the latter. For example, the practice of double-blind experiments—the golden standard of investigating the effectiveness of medicinal drugs and treatments, is an established scientific inquiry procedure developed in response to a core epistemological dimension associated with the theory-laden nature of observation.

The question follows: What perspective is more viable, NOS is scientific practice or NOS is about scientific practice? One possible way to answer this question is to examine the enterprise we call NOS. NOS is a reflective endeavor: The varying images of science that have been constructed throughout the history of the scientific enterprise are, by and large, the result of the collective scholarship of historians, philosophers, and sociologists of science, as well as scientists turned historians or philosophers, and reflective scientists. Representations of the scientific enterprise reflect the collective efforts of these scholars to reconstruct the history, activities, and practice of science in an attempt to understand its workings and the nature of its products. When science educators approach NOS, they do not consult the published writings of practicing scientists. Rather they read and cite the works of philosophers, historians, and sociologists of science, including scientists turned historians or philosophers. To be sure, approaches to studying the scientific enterprise have undergone major shifts, such as from normative to more descriptive, from philosophically-minded histories to historically-minded philosophies, from upholding a firm distinction between the contexts of discovery and justification to blurring this distinction, from studies of polished scientific theory to the study of science-in-action, and from a sole focus on the physical sciences to examining the biological sciences. Nonetheless, the domain of NOS largely remains a field of scholarship for non-practicing scientists. Obviously, there are some active scientists who explicitly address and publish about epistemological issues (e.g., Weinberg 2001). These cases are, nonetheless, exceptions to the rule, and hardly derail the current argument because the overwhelming majority of practicing scientists do not have active research programs that address epistemology of science.

Indeed, as Kuhn (1970) argued, practicing scientists do not engage with reflective and re-constructive activities, and they mostly do not need to. Scientists are trained by apprenticeship in communities of practice that do not generally engage them, at least not consciously or explicitly, with epistemological issues. A quick survey of doctoral programs in various scientific disciplines would show that scientific education rarely includes, if ever, formal coursework in history, philosophy, or sociology of science. Indeed, such programs do not even include formal coursework in research methodology of the sort required of doctoral students in psychology or education. Kuhn (1970) argued that initiating science students into disciplinary traditions includes having them take the processes and methods of those disciplines, and consequently the underlying ontological and epistemological values and assumptions, for granted. Putting aside epistemological and ontological issues, and the conviction that the methods at hand will generate valid and reliable knowledge, advanced students and scientists can engage the activities of their science disciplines and invest the time and energy required to vigorously pursue answers or solutions to specific questions or problems related to some restricted aspect of a minute corner of the natural world. Epistemological and ontological underpinnings do not seem to be crucial to the learning or practice of disciplinary science (at least, according to Kuhn, in periods of "normal" science). For Kuhn, barring periods of intense crises, the very fact that practicing scientists do not tackle epistemological issues is an integral aspect of NOS.

Indeed, the scientist could very well be naïve on issues related to NOS. As Medawar (1969, p. 11) put it:

> Ask a scientist what he conceives the scientific method to be, and he will adopt an expression that is at once solemn and shifty-eyed: solemn, because he feels he ought to declare an opinion; shifty-eyed, because he is wondering how to conceal the fact that he has no opinion to declare. If taunted he would probably mumble something about "Induction" and "Establishing the Laws of Nature."

Scientists are practitioners within well established traditions of practice and cannot be assumed —as the evidence shows—to hold coherent epistemologies of the sort sought in philosophically-oriented inquiries, which underlie our conceptions of NOS (Yore et al. 2004). Thus, it could be seen that while scientific practice provides the context and stuff for investigating epistemological issues, the practice itself is not NOS. NOS is not lived practice. The endeavor to delineate various aspects of NOS is not necessarily a derivative of engaging the practice of science or going through its motions, but rather a matter of putting questions to and reflecting on that practice. NOS is reflection on practice.

Having made the distinction between the two perspectives, the following section explores its implications for influencing and assessing students' and teachers' conceptions of NOS. This examination will serve to show that, irrespective of one's inclination to champion the lived or reflective perspective, empirical evidence seems to weigh on the side of the latter.

Implications of the Lived and Reflective Perspectives

Implications for Influencing Learner Conceptions of NOS

The lived and reflective perspectives on NOS entail very different approaches to influencing students' and teachers' conceptions of NOS. Elsewhere we dubbed these approaches as implicit and explicit approaches, respectively, to teaching about NOS (Abd-El-Khalick and Lederman 2000). From a lived perspective, NOS is practice and can only be acquired implicitly through practice. As Duschl put it, "NOS… cannot be taught directly, rather it is learned, like language, by being part of a culture" (Duschl 2004, as cited in Abd-El-Khalick et al. 2004, p. 412). The lived perspective assumes that precollege students can actually engage in authentic scientific activities akin to those engaged by practicing scientists. Abd-El-Khalick (2008) and Burbules and Linn (1991) explicate the shortcomings of this assumption. Advocates of the lived perspective and implicit approach also assume that learning about NOS would result as a "by-product" of learners' engagement in science-based activities. For example, Barufaldi et al. (1977, p. 291) noted, "Students presented with numerous hands-on, activity-centered, inquiry-oriented science experiences… should have developed a more tentative view of science." Similarly, under the implicit approach, changes in the learning environment are believed to promote learners' understandings of NOS. For instance, Haukoos and Penick (1983, p. 631) noted that if "the instructor assumed a low profile by sitting at student eye level and stimulated discussion of the… materials with questions designed to elicit student ideas" then learners would develop an understanding of the notion that scientific knowledge is not complete or absolute.

By comparison, from a reflective perspective, NOS is about practice and draws on a cognitive body of scholarship that examines scientific practice from a distance. Thus, NOS cannot be learned automatically or implicitly through engagement in doing science, but should rather be consciously addressed as part of the science curriculum through structured reflection on practice, which draws on conceptual tools available in the body of scholarship that we refer to as NOS. Thus, advocates of an explicit approach argue that the goal of enhancing learners' conceptions of NOS "should be planned for instead of being anticipated as a side effect or secondary product" of engagement with science (Akindehin 1988, p. 73). A variety of approaches have been developed under the explicit approach, including the use of history and philosophy of science and explicit reflective NOS instruction to address students' and teachers' NOS views.

If one accepts the argument developed earlier about the very nature of the NOS enterprise, one would conclude that the lived or implicit approach to influencing students' and teachers' NOS views would not be very effective. Of course, the argument could be debated. However, the relative effectiveness of implicit and explicit approaches to NOS instruction could be adjudicated by reference to empirical evidence. First, much of the curricula of the 1960s and 1970s emphasized hands-on, inquiry activities. These curricula assumed that NOS would be learned implicitly through doing science as opposed to requiring explicit attention. However, research studies that focused on the effectiveness of these curricula have consistently indicated that students did not develop the desired NOS understandings (e.g., Tamir 1972). Second, a critical review of the literature shows that explicit approaches were more effective than implicit ones in bringing about substantial changes in science teachers' views of the scientific enterprise (Abd-El-Khalick and Lederman 2000). Thus, empirical evidence does not support the effectiveness of approaches to influencing views of NOS derived from the lived perspective.

Implications for Assessing Learner Conceptions of NOS

The lived perspective entails assessing learners' NOS conceptions from practice, that is, while students are engaged in doing science (Kelly et al. 1998). Irrespective of the form that such an assessment would take, it will involve an inference to beliefs from actions. This approach is apt to be problematic. As noted above, practicing scientists do not necessarily do science in accordance with an articulated epistemological framework; such a framework is rarely explicated in scientific apprenticeships. While scientists' actions might be consistent with an epistemological framework underlying the disciplinary tradition into which they were initiated, these actions might not tell much about a particular scientist's underlying epistemological beliefs. For example, a friend of mine is a computational chemist heavily engaged in university-based pharmaceutical research in which she builds virtual macro-molecules and investigates their stability and interactional properties with certain parts of virtual receptors on cellular surfaces. She is also a devout Christian. In a casual conversation, she indicated that taking communion from the same utensil during Sunday mass cannot result in the spread of orally-transmitted viruses among worshipers because God would not allow such a thing to happen to those engaged in such a holly deed. This is an example of a scientist who believes in supernatural intervention in the course of an established and well understood natural phenomenon, that is, the spread of infectious agents. Many of us can reproduce similar examples in which some scientist's beliefs are not consistent with their daily scientific practice and associated worldview.

Thus, it could be seen that assessments involving inferences to beliefs from actions are based on the shaky assumption that learners' action as they engage in doing science are necessarily reflective of, and consistent with, an underlying epistemological framework. What makes this approach even trickier is the mounting evidence, which indicates that students' epistemological beliefs are fluid, contextual, fragmented, and even outright inconsistent (e.g., Jon Leach et al. 2000). Additionally, like other assessment approaches to epistemological beliefs, inferences to beliefs from actions run the risk of imposing the observer's own epistemological framework on those observed (i.e., creating versus assessing students' conceptions of NOS). One possible result is attributing some coherent framework (e.g., inductivist, hypothetico-deductivist) to students not because they necessarily ascribe to such a framework, but because the observer approaches the task with a number of coherent frameworks in mind (this is the theory-laden nature of observation in action!). This situation is akin to convergent NOS assessment instruments that often indicated that students held some consistent epistemological framework, which later turned out to be a mere artifact of the fact that these instruments were designed with specific epistemological frames in mind (Aikenhead 1988). Of course, approaches using inferences to beliefs from actions could ameliorate this latter concern by having several observers independently examine and compare student practices across several contexts. Still, this assessment approach needs further anchorage. This anchorage, I believe, amounts to engaging students in reflective discourse about their actions and conceptions of NOS.

The reflective perspective on NOS entails that students be engaged in reflective discourse regarding their images of science or beliefs about NOS. This approach has several advantages. First, the issue of whether the approach itself is assessing or creating students' views of NOS is irrelevant because this perspective does not assume that students have well articulated and consistent views of NOS. Rather, the reflective approach assumes that learners' views of NOS are, at best tacit, fragmented, and inarticulate. These views are brought to the forefront, examined and even revised through structured reflection over the course of the assessment in the same way that philosophers, historians, and sociologists of science engage in structured efforts to reconstruct the practice of science to bring aspects of NOS to our attention. Second, by engaging learners in discourse, assessors could follow their lines of thinking and clarify any ambiguities in their statements. While inference is necessarily involved, it is minimized. Assessors could test their inferences about learners' NOS views on-the-spot through continued discourse. Third, assessors could explore the degree to which learners' views are consistent through triangulation: A certain aspect of NOS could be assessed using a variety of prompts and by reference to several contexts. Our approach (Lederman et al. 2002) provides one possible form for assessing NOS conceptions from the reflective perspective.

Of course, one shortcoming of the reflective approach is the extent to which learners and assessors know and are familiar with the contexts in which the views about NOS are elicited and will necessarily be anchored. This could provide a useful juncture to meaningfully link both approaches to the assessment of NOS views: Students could be engaged in reflective discourse about their own practice and the ideas they construct instead of reference to the practice of scientists and canonical scientific knowledge. However, there are, at least, two disadvantages to such an approach. First, as the contexts invoked for reflection are apt to be very idiosyncratic, cross-study comparisons would be difficult. Second, some attributes of NOS can hardly be situated in short-lived science-related student practice. These aspects include, for example, the nature of scientific theory and law, and the tentativeness of scientific claims, which become apparent through examination of relatively long periods in the history of science.

It should be noted that the reflective perspective on NOS entails that engaging learners with authentic scientific practice and inquiry activities provides the ideal context for influencing and assessing their NOS views. However, while necessary, this engagement is not sufficient. Engagement needs to be coupled with reflection. This is somewhat different from the consequences of the lived perspective, in which engagement with authentic scientific practice and activities is teaching about, and assessment of, NOS.

A Developmental Explicit-Reflective Framework for Addressing NOS in Science Education

Several crucial components of the proposed framework have already been outlined above. These components include, first, conceptualizing NOS as a reflective endeavor. NOS embodies a cognitive body of works representing the collective efforts of scholars engaged with the systematic study of science from—among other lenses—philosophical, historical, and sociological lenses. Thus, while focused on scientific practice, NOS cannot be reduced to practice. Teaching and learning about NOS in science classrooms entail internalizing understandings about science derived from this body of scholarship. Second, the framework extends the approach underlying current reform documents in science education, which highlights generalized agreements about NOS and disregards controversial areas. This is achieved by focusing on currently emphasized aspects of NOS that are, nonetheless, addressed at increasing levels of depth along a developmental continuum from a treatment that is general, simple, and unproblematic at the elementary school level to one that is specific, complex, and problematized (or controversial) in science teacher education settings (see Table 69.1). Such an approach addresses the pragmatic need to present precollege students with more accurate conceptions of NOS while remaining faithful to the current status of our understandings about NOS. The implications of the framework for influencing and assessing learner conceptions of NOS have also been touched upon. In particular, the importance of the generative nature of NOS assessments and the issues underlying assessment approaches that purport to make inferences from practice to beliefs about NOS were discussed. Additionally, the proposed framework entails an explicit-reflective approach to addressing NOS instructionally in science classrooms. Some brief comments about this latter approach are in order.

An explicit-reflective approach to NOS instruction should not be equated or confused with didactic instruction. The explicit-reflective approach, first introduced by Abd-El-Khalick et al. (1998) and then expanded and refined (e.g., Abd-El-Khalick 2001, 2005), represents an overarching framework to help guide instruction about NOS.

The label "explicit" is curricular in nature, while the label "reflective" has instructional implications.

Thus, far from referring to direct or other modes of didactic instruction, the label explicit emphasizes the need for including specific NOS learning outcomes in any instructional sequence aimed at promoting NOS understandings. As is the case with learning about science content or developing science process skills, learning about NOS should be intentionally planned. The inclusion of specific NOS learning outcomes in curricula does not entail a specific instructional approach, be it direct or inquiry-oriented. Science curricula and instructional materials put forth specific learning outcomes related to complex scientific theories, principles, and ideas that, nonetheless, end up being addressed using a range of pedagogical approaches including those that are active, student-centered, collaborative, and/or inquiry-oriented in nature. Choosing a specific pedagogical approach often depends on a number of factors, including the instructional outcomes themselves; the characteristics, abilities, interests, and skills of the learners; available resources; and the educational milieu. Our strong preference would be for choosing pedagogical approaches that are active, student-centered, and collaborative in nature, as well as embedded in science content and authentic inquiry-oriented experiences (e.g., Abd-El-Khalick 2001).

The reflective component, nonetheless, does entail instructional elements to be incorporated into pedagogical approaches undertaken from within the explicit-reflective approach. There is need for the provision of structured opportunities designed to encourage learners to examine their science learning experiences from within a NOS framework. This latter framework would focus on questions related to the development and validation, as well as the characteristics of, scientific knowledge. In our own work, this reflective component had often taken the form of questions or prompts embedded within science learning activities (e.g., Khishfe and Abd-El-Khalick 2002), as well as synthesis activities, such as writing reflection papers in response to specific NOS-related cues (e.g., Abd-El-Khalick 2005).

A final and significant question remains: Can the lived and reflective perspectives be reconciled to work in synergy? I believe yes. Researchers working within these two perspectives could capitalize on and benefit from each others' work if the subtle, though significant, difference in perspective is worked out through continued discourse. As emphasized above, engagement with authentic science or inquiry-based activities is not sufficient for learning, or assessing learner views, about NOS. Nonetheless, such engagement is necessary. This component is crucial to achieving synergy between the two perspectives. Advocates of the lived perspective need to realize that while their approach fosters the development of crucial content understandings, inquiry skills, and habits of mind, they fall short of actually addressing NOS because the critical component of reflection on practice is wanting. Similarly, they need to realize that making inferences about learner conceptions of NOS from practice without additional anchorage in generative forms of learner discourse entails significant threats to the validity of the assessments. By the same token, those who attempt to address NOS explicitly without meaningfully embedding their approach in science content and/or authentic science inquiries will most likely fail to convey to students more than superficial platitudes about the characteristics of scientific knowledge and the assumptions underlying its development. Similarly, generative assessments of learner views of NOS that are not anchored in specific science content or inquiry contexts will also suffer validity issues resulting from difficulties of interpreting learner responses that are necessarily contextual. If these mutual understandings are achieved, then we can significantly advance research and development efforts related to NOS. This is especially the case because significant questions remain to be answered in relation to, among many other things, the developmental appropriateness of the target NOS aspects for precollege students and their implications for the aforementioned developmental approach to addressing NOS aspects, effective ways to embed NOS in science content instruction and inquiry activities, developing science teachers' pedagogical content knowledge for teaching about NOS, helping teachers negotiate a host of mediating factors that seem to impede their implementation of science instruction that is consistent with what we know about NOS, and the relationship between learners' views of NOS and their learning of science content and engagement with inquiry activities.

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