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Two Views About Explicitly Teaching Nature of Science

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Abstract Our focus is on the effects that dated ideas about the nature of science (NOS) have on curriculum, instruction and assessments. First we examine historical developments in teaching about NOS, beginning with the seminal ideas of James Conant. Next we provide an overview of recent developments in philosophy and cognitive sciences that have shifted NOS characterizations away from general heuristic principles toward cognitive and social elements. Next, we analyze two alternative views regarding 'explicitly teaching' NOS in pre-college programs. Version 1 is grounded in teachers presenting 'Consensus-based Heuristic Principles' in science lessons and activities. Version 2 is grounded in learners experience of 'Building and Refining Model-Based Scientific Practices' in critique and communication enactments that occur in longer immersion units and learning progressions. We argue that Version 2 is to be preferred over Version 1 because it develops the critical epistemic cognitive and social practices that scientists and science learners use when (1) developing and evaluating scientific evidence, explanations and knowledge and (2) critiquing and communicating scientific ideas and information; thereby promoting science literacy.

1 NOS and Science Education

When and how did knowledge *about* science, as opposed to scientific content knowledge, become a targeted outcome of science education? From a US perspective, the decades of interest are the 1940s and 1950s when two major post-war developments in science education policy initiatives occurred. The first, in post secondary education, was the GI Bill

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that enabled military veterans to pursue university studies. A concomitant event was the development of the General Education course based on *Harvard Case Studies in History of Science* that provided non-science majors entering the post WWII world of science and technology with a foundational appreciation for the tactics and strategies of science. The second development was the creation of the National Science Foundation (NSF) that, in its first decade during the 1950s, funded science and mathematics curriculum and instruction development programs. The emphasis of the high school curriculum was on preparing future scientists through teaching science as inquiry and engaging students in thinking like scientists.

The decades from 1950 to 1980 also represent a period of significant changes in thinking about the nature of science and science education. New views of philosophy of science, of psychology of learning and of pedagogical principles contributed to a questioning and rejection of received views (i.e., logical positivism in philosophy, behaviorism in the learning sciences). In philosophy the influence of history of science in the 1950s ignited the historical turn in philosophy of science. The seminal work of T. S. Kuhn's (1970) *The Structure of Scientific Revolution, 2nd Edition* represents a turning point. Quickly the focus of philosophers of science shifted to matters concerning the structure of theories and the process of theory development (Suppe 1977).

In psychology the influence of cognitivism challenged the dominant behaviorism as a framework for guiding science education. During the 1960s Piaget's ideas about child development and Vygotsky's ideas about sociocultural development were major agents of change. In fact, Kuhn invokes Piaget's ideas of conceptual change in *Structures*. Within a decade with the emergence of cognitive information-processing psychology there would be debates about domain-general versus domain-specific modes of learning when comparing and contrasting the ideas of Piaget and Vygotsky (Duschl and Hamilton 2011).

In pedagogy the NSF science curriculum that focused on contemporary science and on inquiry approaches strongly influenced the teaching and learning of science. The NSF curriculum programs began with High School courses and within a decade would reach back to include science curriculum programs for grades K-8 grade. We examine these two initiatives and the impact on NOS in more detail below. Here we want to frame the broader contexts that have led (1) to the inclusion of NOS in K-12 science education and (2) to the competing perspectives regarding the content and teaching of NOS.

The focus on 'doing science' led to the vision that science education should be conceptualized as an 'enquiry into enquiry' (Schwab 1960). Engagement with phenomena through experiments, demonstrations, and focused observations became the 'inquiry approach' to teaching and learning science. The agenda for the NSF alphabet curricula was a K-12 program of study that focused on 'science for scientists.' The USSR launching of Sputnik had kick started the US Congress into action and the funding for science and mathematics educational reform was substantial (Duschl 1990; Rudolph 2002).

The decade of the 1970s was a turbulent time for US science education. NSF was funding numerous programs where teachers were being trained on the implementation of the NSF curriculum materials Political challenges that NSF was promoting a national curriculum led to the demise of NSF supported teacher professional development programs (DeBoer 1991; Duschl 1990; Rudolph 2002). Congress responded by pulling the plug on NSF funding for teacher training. But by the 1980s the US economy wasn't competing well with other countries in the emerging global markets. Once again the US Congress was stirred to action to respond to the problem that a science and technology economy and military needed a workforce that could function in work environments where computer and robotic technologies and information processing were increasingly prevalent.

Table 1 Science standards and science literacy goals

NRC (1996) National Science Education Standards	AAAS (1993) Benchmarks for science literacy
1. Unifying concepts and processes in science	**1. The nature of science**
2. Science as inquiry	2. The nature of mathematics
3. Physical science	3. The nature of technology
4. Life science	4. The physical setting
5. Earth and space science	5. The living environment
6. Science and technology	6. The human organism
7. Science in personal and social perspectives	7. Human society
8. History and nature of science	8. The designed world
	9. The mathematical world
	10. Historical perspectives
	11. Common themes
	12. Habits of Mind

The 1980s was the decade where the Standards movement begins with a goal of setting out what students should know and be able to do. By the 1980s the agenda for science education began to shift away from a focus on 'science for scientists' to a broader more embracing 'science for all' focus as a goal. Research in the cognitive sciences established cognitive models of learning that could be used to guide instruction and the assessment of learning. Two documents one from the National Research Council (NRC 1996) *National Science Education Standards* and one from the American Association for the Advancement of Science (AAAS 1993) *Benchmarks for Scientific Literacy* were developed and subsequently used by states as the basis for science curriculum. They were also used by the National Assessment Governing Board for a redesign of NAEP (National Assessment of Educational Progress) Science exam that is given every 4 years to a nationally representative sample of 4th, 8th, and 12th grade students. Important to note for our discussion of NOS is the inclusion by the NRC (1996) *NSES* document and the AAAS (1993) *Benchmarks* document designations for history and nature of science and for unifying/common concepts, themes and processes in science (See *bolded* items in Table 1).

The upshot for science education is that a lively debate about characterizing and teaching 'What is Science' developed. The issues surround whether or not to revise interpretations of NOS in response to the "continuing debates among historians, philosophers and sociologists of science which are invoked to undermine the currently widely accepted, domain-general, consensus-based aspects approach to NOS" (Abd-El-Khalick 2012, p. 353). On one side of the debate, and the basis for Version 1 presented below, is the position that NOS should be benchmarked using domain-general, consensus-based aspects of NOS and taught through explicit references to a set of heuristic principles[1] that philosophers and historians of science use to characterize science as a way of knowing (c.f., Holton 1978; Lakatos 1970; Laudan 1977).

On the other side of the debate, and the basis for Version 2 below, is the position that science, as well as science education, should be conceptualized in terms of cognitive, epistemic, and social practices (Giere 1988; Nersessian 2002) and the material and technological contexts (Pickering 1992) that characterize doing science. The Version 2 science

[1] Examples include Lederman et al. (2002), McComas and Olson (1998), Niaz (2009), Osborne et al. (2003), Wenning (2006).

education position is that NOS learning occurs when students' engagements are situated in these practices, in age appropriate contexts.[2]

At the core of the debate is what comes to be seen as 'explicit' teaching of NOS. Version 1 advocates that teachers explicitly link the consensus statements to features of science lessons and activities. Version 2 advocates students engage in domain-specific scientific practices during weeks or months long curriculum units that focus the learners' attention on the model building and refining enactments found in measuring, observing, arguing from evidence and explaining that are part of the growth of scientific knowledge.

Our position is the 'explicit' issue hinges on the philosophical perspectives one adopts and/or omits to characterize the growth and development of scientific knowledge. Our interpretation is that Version 1 is grounded in the rational reconstruction philosophy of science that emerged as a response to Thomas Kuhn's historical-turn in *Structures*. An examination of the positions developed (i.e., separation of inquiry and NOS) by and of the philosophical references found in Abd-El-Khalick (2012) and Schwartz et al. (2012) supports our interpretation. Central to these historical turn philosophers and historians is a defense of science as a rational and objective way of knowing. Version 2 we see as grounded in the 'Naturalized View of Philosophy of Science' that emerged among philosophers of science as another response to the historical turn. A passage from the introduction of Carruthers et al. (2002) captures well the current consensus among contemporary philosophers of science:

> It became important, then, to see science, too, as a natural phenomenon, somehow recruiting a variety of natural processes and mechanisms—both cognitive and social—to achieve its results. Philosophers of science began to look, not just to history, but also to cognitive psychology in their search for an understanding of scientific activity. (Carruthers et al. 2002, p. 4)

Our goal is to argue that Version 2 is the more psychologically, philosophically, and pedagogically sound approach for teaching science and teaching about science. We believe students should learn through experience what it means to be rational and objective, and not to simply accept those adjectives as descriptors of science.

We begin with three review sections. In the first, we present overviews of recent developments in science education research and policy and in philosophy of science. In the second, we examine post-secondary education developments in teaching about the nature of science beginning with James Conant effort as Harvard. In the third review section, we examine secondary education NOS developments and measures over the ensuing decades. We then turn our attention to an examination of 'Explicit NOS Instruction' and discussions of Versions 1 and 2. In the conclusion, we give an overview of three research programs that have adopted Version 2 orientations and then discuss implications for science education.

2 Recent Developments in Science Education and Philosophy of Science

2.1 Science Education Research and Policy

The agenda for science education has broadened in ways that demand a rethinking of approaches to curriculum, instruction, and assessment. The last 50 years has seen rapid growth of scientific knowledge, tools/technologies, and theories. Like the first science education reformers in the 1950s and 1960s, we are faced today with the challenge of

[2] Proponents include Allchin (2011), Ault and Dodick (2010), Duschl (2000), Duschl and Grandy (2008), Ford (2008), Van Dijk (2011).

making important decisions about what and how to teach. But unlike the 1960s reform effort we now have a deeper understanding of how and under what conditions learning occurs (NRC 2007, 1999; Sawyer 2006). We also have a richer understanding of the dynamics occurring in the growth of scientific knowledge. Essentially, we have learned about learning through advancements in two scholarly domains that can help us in our thinking about how to reform K-12 science education:

- 'Learning Sciences'—a group of disciplines focusing on learning and the design of learning environments that draw from cognitive, developmental and social psychology, anthropology, linguistics, philosophy of mind, artificial intelligence, and educational research.
- 'Science Studies'—a group of disciplines focusing on knowing and inquiring that draw from history, philosophy, anthropology, and sociology of science as well as cognitive psychology, computer science, science education, and artificial intelligence.

The advancement of the learning sciences (Sawyer 2006) and our deeper understanding of children's cognitive development (NRC 2007) has led us to recognize and seek coordination of a triad of practices—cognitive, epistemic and social—in the learning of science. The strong recommendation from *Taking Science to School* (*TSTS*) (NRC 2007) is that acquiring conceptual knowledge (e.g., content) should not be separated from learning science practices (e.g., processes). The emerging consensus is that science learning and teaching ought to be grounded in epistemological, social structures, and practices. Within science education, changes in our understandings of what is science—the nature of science—have influenced our understandings of what's involved in learning and doing science. Conversely, our understandings of what's involved in learning and doing science have influenced our understandings about the nature of science.

TSTS (NRC 2007) recommends science instruction move away from domain-general principles and instead be organized around select conceptual knowledge frameworks and practices. Current research in cognitive development and philosophy of mind suggests that very young children have a surprising capacity for reasoning and considerable prior knowledge in select domains (cf., Keil 1989; Subrahmanyam et al. 2002). The current research on cognitive development and reasoning in science also demonstrates that context matters both in terms of content, learning environment and learning goals (Atran 2002; Koslowski and Thompson 2002; Siegal 2002). That is, learning is linked to the domain within which learning is taking place and dependent on the acquisition of select practices and ways of representing and communicating science ideas and critiques.

This scholarly work reveals how infants and young children are capable of abstract reasoning in core knowledge domains of science and mathematics. The research reported in *TSTS* (NRC 2007) reveals that children ages 3–5 are capable of complex reasoning when they are provided with multiple opportunities that sustain their engagement with select scientific practices over time. These include predicting, observing, testing, measuring, counting, recording, collaborating, and communicating. The research also shows that there are selected contexts and conceptual domains that facilitate the development (1) of conceptually linked learning, (2) of science language learning and (3) of science inquiry practices learning. Some of the core domains are:

- Simple mechanics of solid bounded objects.
- Behaviors of psychological agents.
- Actions and organization of living things.
- Makeup and substance of materials.

Thus, we know from the research that children in the first several years of schooling are capable of abstract reasoning within select domains. The reasoning-lean curriculum approaches typically found in use today (1) tend to separate reasoning and learning into discrete lessons thus blurring and glossing over the salient themes and big ideas of science; thus making curricula “a mile wide and an inch deep” (Schmidt et al. 1997) and (2) in the case of middle school textbooks, tends to present science topics as unrelated items with little or no regard to relations among them (Kesidou and Roseman 2002). Hence, the recommendation from the *TSTS* (NRC 2007) report is that longer coherent sequences of teaching (referred to as learning progressions) should be the basis for K-8 science learning. The recommendation for learning progressions represents a shift in emphasis from teaching that focuses on what we know (e. g., facts and skills) to teaching that focuses on how we came to know and develop scientific knowledge and on why we believe what we know in contrast to alternatives.

The emphasis on how and why reflects the *TSTS* recommendation that science learning needs to be strongly grounded in the use of evidence. This, once again, leads to the recommendation that science learning be connected through longer sequences of instruction (e.g., learning progressions) that function vertically across and horizontally within and years of instruction. The rationale is to facilitate the learning of core science knowledge and practices that are critical for development of scientific knowledge and knowledge about science. Developing rich, conceptual and epistemic knowledge takes time and requires instructional-assisted support, i.e., mediation from teachers and/or peers. The research suggests that the modularization of science units and the separation of concept learning from practices requiring use of knowledge does not promote meaningful learning.

2.2 Path to Naturalized Philosophy of Science

The parade of the sciences over the last 300 years has been dynamic, to say the least. New tools, technologies and theories have shaped science pathways first in physics and chemistry for the early paradigmatic sciences; in population biology through Darwinian Evolution, the Great Synthesis and on to molecular biology and medical sciences; in quantum mechanics; in material, communication and information sciences; in geosciences and Earth systems sciences; in neurosciences and brain sciences, to name but a few. Reflection on these advances in science has spawned multiple philosophical perspectives to describe and account for the growth of knowledge. Over the last 100 years there have been three major movements in philosophy of science, each with its internal conflicts and varieties.

1. The formal-based hypothesis testing view that gave us Logical Positivism, Logical Empiricism and Deductive-Nomological explanations to account for the justification of scientific knowledge claims.
2. The history-based view of theory development and conceptual change that gave us Paradigms, Research Programmes, Heuristic Principles, Scientific Thema, and Research Traditions to account for the rational growth of scientific knowledge.
3. The model-based view of cognitive and social dynamics among communities of scholars that gave us social epistemology, naturalized philosophy of science, and accompanying epistemologies to account for the deepening and broadening of scientific explanations.

The Logical Positivist movements arose from the successes of formal logic in clarifying and making rigorous the foundations of mathematics. These movements wanted to extend these successes to the sciences. Although the Vienna Circle is the best known of the groups, there were parallel groups in Warsaw and Berlin. These thinkers primarily aimed at clarifying the relation between observations and laws and theories by defining rigorously the extent to which specific observations confirm or disconfirm a law or theory. As a byproduct of this project, a solution to the demarcation problem would follow: a statement is meaningful just in case it is susceptible of either confirmation or disconfirmation. Ernst Mach inspired many of the ideas of the groups, but the best known are those of Carnap, Hempel, Neurath and Reichenbach. For our purposes, the two most important tenets of these groups are that there is a class of observation statements which provide an unproblematic foundation, and that the project of philosophy of science is limited to understanding finalized theories, not the processes by which scientists arrive at them (Reichenbach 1938).

The second movement introduced three new elements—analyses of the historical development of theories and their relation to evidence, the realization that observation cannot be taken as a simple and unproblematic concept, and the significance of the scientific research community. It also saw the demise of the assumption of the earlier movement that the assessment of the support that evidence provides for a theory can be reduced to a precise algorithm whose correctness can be proved. The assumption of this possibility was an extrapolation of the near total success of mathematical logic in analyzing mathematical proof. It is ironic that the most philosophically significant result in the foundations of mathematics was Godel's incompleteness theorems that demonstrated rigorously that, although the project was largely successful, it was necessarily impossible to carry out completely. This negative result seems not to have dampened enthusiasm for extending the program to science.

The historical studies showed that theories were not well modeled by static formal sentences but were developed over time by the research community in response to evidence, both positive and negative. They also showed that the relevant research communities were diverse in their opinions and values, and that the choice between theories seemed at times to be a matter that was contingent on social or economic factors. In some cases, old concepts were very resistant to replacement by new, and the process seemed sometimes to be abrupt when matters reached a tipping point.

The earlier idea of an observation sentence, a statement that reported the contents of a sense experience without any tinge of interpretation was belied by both history of science and perceptual psychology. Many of Galileo's critics had the experience of seeing the sun move at sunset and of seeing heavy objects falling faster than lighter objects. Gestalt experiments and ambiguous figures showed that even the most basic reports could be observer dependent. Historical analyses of major transitions, such as the Copernican Revolution, revealed that in those transitions, contrary to the steadily cumulative view of science, what seemed to be facts changed and little if any of previous theories remained. The Earth came to be seen as a planet, the sun as a star!

Kuhn's *Structure of Scientific Revolutions* presented the most influential of the alternative pictures in this period, although most of the elements in *Structure* can also be found in other more-or-less contemporary writers such as Feyerabend, Hanson, Toulmin and others. Kuhn's essay produced many important reactions, some positive and some oppositional. In science education, one of the most important outcomes was the "conceptual change" movement, based in the idea that students are not blank slates on which science teachers imprint the truths, but that students arrive with many preconceptions at odds with currently accepted science. This shift accompanied the movement from behaviorism to more cognitively oriented views of psychology and learning.

The third movement, naturalized philosophy of science, emerged as an alternative to the historical turn by looking more carefully at the cognitive and social practices and the material worlds of scientists. In addition to revisiting old historical developments, such as the Copernican Revolution and the emergence of chemistry from alchemy, historians and philosophers attended to the histories of newly emerging branches of science and technology. Contemporary philosophical accounts of the growth of scientific knowledge [e.g., Knorr-Cetina's (1999) epistemic cultures] have adopted naturalistic accounts to explain the emergence of new conceptual (what we know), methodological (how we know), and epistemological (why we believe) criteria or standards for the growth of scientific knowledge and the mechanisms of scientific reasoning.

> It became important, then, to see science, too, as a natural phenomenon, somehow recruiting a variety of natural processes and mechanisms—both cognitive and social—to achieve its results. Philosophers of science began to look, not just to history, but also to cognitive psychology in their search for an understanding of scientific activity. (Carruthers et al. 2002, p. 4)

Developments in scientific theory coupled with concomitant advances in material sciences, engineering and technologies have given rise to radically novel ways of observing nature and engaging with phenomenon. At the beginning of the twentieth century scientists were debating the existence of atoms and genes, by the end of the century they were manipulating individual atoms and engaging in genetic engineering. These developments have altered the nature of scientific inquiry and thus greatly complicated our images of what it means to engage in scientific inquiry. Today scientific inquiry is guided by highly theoretical beliefs that determine the very existence of "observational" events (e.g., neutrino capture experiments in the ice fields of Antarctica). Scientists and engineers don't just observe phenomena they often produce them.

One important finding from the science studies literature is that conceptual frameworks and methodological practices both change over time. Changes in methodology are a consequence of new tools, new technologies and new explanatory models and theories that, in turn, will continue to shape scientific knowledge and scientific practices. Another finding is that the dialogical processes of theory development and of dealing with anomalous data occupy a great deal of scientists' time and energy. The logical positivist's "context of justification" is an idealized formal final point—the end of a journey; moreover, it is a destination few theories ever achieve, and so emphasis on it entirely misses the importance of the journey. The contemporary understanding of the nature of science holds that the majority of scientists' engagement is not individual efforts toward final theory acceptance, but communities of scientists striving for theory improvement and refinement. What occurs in science is neither predominantly the context of discovery nor the context of justification but the intermediary contexts of theory development and conceptual modification. Importantly, the journey involved in the growth of scientific knowledge reveals the ways in which scientists respond to new data, to new theories that interpret data, or to both. Thagard's (2007) eloquently elaborates on the dynamics of these practices as they relate to achieving explanatory coherence. Advancing explanatory coherence, he argues, involves theories that deepen and broaden over time by respectively accounting for new facts and providing explanations through accounts of mechanisms of why the theory works.

2.3 Naturalized Philosophy of Science

The developments in history of science, the ascendance of cognitive psychology as a successor to behaviorism and acknowledgment of the relevance of the social aspects of science, i.e., the scientific community and sciences place in the larger culture, all appeared as somewhat separate developments in the 1970s and 1980s. Subsequently, the naturalistic turn in philosophy of science has shown how they fit together, as well as introducing three further elements. The key element, obvious in retrospect, is that science is done by scientists and scientists are humans. The basic human cognitive capacities have not changed in the last six hundred years (or six thousand or sixty) but science has.

The fundamental point is that humans are capable of constructing elaborate and powerful theories and technologies and understanding these capabilities involves understanding human invention and use of instruments, technical languages, social structures and learning environments. Two of the new elements in our understanding are an appreciation for the developmental sequence of human cognition and the multifarious value of models. The value of models, aids to cognition that give useful approximate representations were totally missing from the logical positivist picture and mostly omitted from the writers in the historical turn (except Hesse 1966).

Ideas from the interdisciplinary research communities of *learning sciences* and *science studies* extend our understandings of science learning, science practices, scientific knowledge, and scientific discourse (Duschl 2008; Duschl and Grandy 2008). Consider the following core questions posed by Carruthers et al. (2002) from an edited volume examining the cognitive basis of science: "[W] hat makes science possible? Specifically, what features of the human mind, of human cognitive development and of human social arrangements permit and facilitate the conduct of science?" (p. 1) The editors go on to state that such questions are interdisciplinary in nature thus "requiring co-operation between philosophers, psychologists, and others in the social and cognitive sciences [and] as much about the psychological underpinnings of science as they are about science itself." (p. 4)

Cognitive, historical, sociological, and anthropological studies of individuals in knowledge building contexts reveal the importance of practices to the professional activities in these knowledge growth communities. With respect to the scientific disciplines, cognitive models of science (Giere 1988; Goldman 1986; Kitcher 1993; Thagard 1992) coupled with sociocultural characterizations of science (Knorr-Cetina 1999; Kuhn 1970; Longino 1990, 2002) have established the importance that models and modeling, visual representations, knowledge exchange mechanisms and peer interactions have in the refinement of knowledge. The third new feature is that doing science is situated in complex settings of cognitive, epistemic and social practices. These activities and practices progress from experiments to models and then to explanatory theories, or almost equally often, from theories to models or from models to experiments. Naturalized philosophy of science views of science and science learning is fundamentally an enterprise of model building and refining, models being seen as cognitive tools situated between experiments and theories (Giere 1988, 2002; Nersessian 2002, 2008a, b).

The synthesis research report *Taking Science to School* (NRC 2007) takes the position that the teaching and learning of science should be based on an image of science that sees the growth of knowledge as involving the following epistemic and social practices:

1. Building theories and models,
2. Constructing arguments,
3. Using specialized ways of talking, writing and representing phenomena.

This tripartite perspective on school science reflects a synthesis of ideas about the growth of knowledge and the nature of scientific reasoning taken from the learning sciences community and from the science studies community. This perspective also frames one version for explicitly teaching the nature of science which we take up in the next section.

Our deeper understanding of children's cognition reveals "students learn deeper knowledge when they engage in activities that are similar to the everyday activities of professionals who work in a discipline" (Sawyer 2006, p. 4). This perspective on the importance of activities is also found in critiques of logical positivism:

> [P]hilosophy of science had been conducted in a relatively a priori fashion … with philosophers of science just thinking about what scientists *ought* to do, rather than about what they actually *do* do. This all began to change in the 1960s and 1970s, when philosophy of science took its so-called "historical turn." [Emphasis in original] (Carruthers et al. 2002, p. 3)

Philosophers started to realize that any attempts to account for the growth of scientific knowledge or theory change needed to view science inquiry as natural human mental processes and human modes of acquiring knowledge. Understanding what characterizes expertise, examining how representations are constructed and used, and describing the complex cognitive process in problem solving, data modeling, and examining complex systems are some of the natural practices scientists employ. Questions about 'How Science Works and How to Teach It?' would obviously have different answers depending on the perspectives one holds about the tactics and strategies of science, to put it in Conant's terms. The above overviews detail how philosophy of science, like science itself, progressed with time. The three major movements in philosophy of science, each with its internal conflicts and varieties, serve as a guide for examining the various representations of and debates about NOS in school science. We now turn to the debate regarding how to teach the nature of science.

3 NOS Development in Post-secondary Education

The NOS catalyst in post-secondary education was Harvard University and its President James Conant's project to base science education for returning GIs on historical cases studies of select scientific episodes (e.g., Boyle's Laws, Newton's Laws, among others). In the 1950s and 1960s, Harvard University was a center of activity in history of science (HOS). Scholars such as I. B. Cohen, Gerald Holton, Stephen Brush, James Rutherford, Fletcher Watson, William Cooley, Leo Klopfer, Wayne Welch and Glen Aikenhead, among others, were at Harvard between 1950 and 1970 and all contributed to the development of science education instructional materials and/or research activities. Conant's development of the *Harvard Cases in History of Science* (Conant 1957) undergraduate curriculum set the tone and the vision for other Harvard-based science education reform efforts such as the NSF supported high school course *Harvard Project Physics* (1968–1969). Noteworthy, is Thomas Kuhn's earlier involvement as a writer for several cases in physics (e.g., Newton's Laws). Here is where he began to build ideas that led to his seminal publication—*The Structure of Scientific Revolutions*.

Harvard Cases in History of Science and *Project Physics* (Holton et al. 1970) adopted an historical approach to offer science to non-majors. Both projects were based on ideas put forth by James Conant. His *On Understanding Science: A Historical Approach* (1947) set out an agenda and the rationale for a science course that focused on knowledge about science as opposed to scientific knowledge. Anticipating that science, engineering and technology would change society Conant reasoned that science education for non-scientists (e.g., lawyers, teachers, writers, civil servants, businessmen, etc.) was vitally important. He also reasoned that it would be beneficial to clarify popular thinking about the methods of science and concluded that the best way to do so would be to use simple case histories.

The case histories would examine the cultural assimilation of science in the New Age of machines and experts along with some understanding of science. Thus, understanding the tactics and strategies of science was to become the goal of science education for non-scientists.

> The stumbling way in which even the ablest of the early scientists had to fight through thickets of enormous observation, misleading generalizations, inadequate formulations and unconscious prejudice is the story which it seem to me needs telling. (Conant 1947, p. 15)

To present the tactics and strategies of science Conant recommended, "The case histories would almost all be chosen from early days in the evolution of the modern discipline." (p. 17) His list included: Physics—seventeenth and eighteenth Centuries; Chemistry—eighteenth and nineteenth Centuries; Geology—early nineteenth Centuries and Biology—eighteenth and nineteenth Centuries. The criteria for case selection included:

1. Progress had been substantial in the last century.
2. In terms of changing concepts and evolving conceptual schemes, the results of experiments and observations ought to lead to new experiments and observations.
3. Illustrate principles—one or more of the Tactics and Strategies of Science.
   - The evolution of new conceptual schemes as a result of experimentation.
   - Advances in science, e.g., progress.
   - Distinction between advances in mechanical contrivances or primitive chemical process (metallurgy or soap making) and advances in science.
   - Symbiotic nature of science and industry, e.g., agriculture, medicine.

There was skepticism though on Conant's part that recent philosophical analysis had led to an accurate understanding of science. Conant and colleagues were developing the course at a time when the Logical Positivism agenda of examining science through the lens of formal logic held sway. As discussed in the previous section, the *TSTS* commitment to scientific practices can be viewed as a resurrection of Conant's ideas about tactics and strategies. This perspective on the importance of practices is also found in contemporary critiques of logical positivism:

> [P]hilosophy of science had been conducted in a relatively a priori fashion … with philosophers of science just thinking about what scientists *ought* to do, rather than about what they actually *do* do. This all began to change in the 1960s and 1970s, when philosophy of science took its so-called "historical turn." [Emphasis in original] (Carruthers et al. 2002, p. 3)

4 NOS Development in Secondary Education

The launching in 1957 of the USSR satellite Sputnik catalyzed change in K-12 science education. US science, engineering and government were embarrassed. Within one decade, hundreds of millions of dollars were invested in the development of curriculum and facilities, employing top down processes of high school courses first followed by middle grades and elementary grades. Once the curricula were established, NSF funding was directed to teacher institutes to prepare staff to teach these new inquiry-based science programs. Scholarly writings about this pivotal science education period can be found in *Scientists in the Classroom* (Rudolph 2002), *The History of Science Education* (DeBoer 1991), and *Restructuring Science Education: The Role of Theories and Their Importance* (Duschl 1990).

The initial inclusion of nature of science as a learning goal for secondary education came from Harvard, too not surprisingly. Toward the end of the 1950s Leo Klopfer adapted the *Cases* for use in high schools (Klopfer and Cooley 1963) and he also participated in developing the first instrument for assessing understandings about science—test on understanding science (TOUS) (Cooley and Klopfer 1961, 1963). TOUS was a 60 item multiple-choice instrument with three themes that also focus on the tactics and strategies used in science:

1. Understandings about scientists:
   - Generalizations about scientists as people.
   - Institutional pressures on scientists.
   - Abilities needed by scientist.
2. Understandings about scientific enterprise:
   - Communication among scientists.
   - Scientific societies.
   - Instruments.
   - International character of science.
   - Interaction of science and society.
3. Understanding about the methods and aims of science.
   - Theories and models.
   - Controversies in science.
   - Science and technology.
   - Generalities about scientific method.
   - Unity and interdependence of the sciences.

The TOUS was the first assessment of knowledge *about* science. Over the next three decades a wide variety of instruments were developed to assess students' understandings of, and attitudes toward, science as a way of knowing. "Appendix 1" presents several prominent NOS assessments with information on NOS themes, targeted audience, and sample items. All but one employ survey, multiple choice or short response formats examining features of science. The Nature of Science Interview (Carey and Smith 1993) is distinct in that it probes through a structured interview epistemological understanding about the role experiments and theories have in the growth of scientific knowledge.

As mentioned above, in the US watershed events for science education were the publication of the AAAS *Benchmarks of Science Education* and the NRC *National Science Education Standards*. Each, in very different ways, incorporates HOS and NOS into their frameworks for the design of state science standards, thus reinforcing the need for measures of learning to guide instruction and thereby fixing views about the nature of science and of inquiry. Our review of the various NOS measures listed in Appendix 1 reveals that a common denominator was establishing a set of topics, themes, or views that would inform and guide the assessment of student learning and the design of curricula.

It is important to recognize the wide diversity among the NOS measures that reflect the evolution of thinking in philosophy of science and learning theory. A good proxy for capturing these changes is to consider the 40-year evolution of various US National Science Teachers Association (NSTA) position statements that were analyzed by one of us (Duschl) for statements regarding NOS, Nature of Inquiry and Images of Child Development obtained from NSTA archives (www.nsta.org/about/positions) and old issues of *The Science Teacher*. (See "Appendix 2"). The chronological changes to the NSTA statements demonstrate how views about NOS, inquiry, and learning have shifted to consider Kuhn's 'historical turn', the dynamics of theory change in science, and constructivist models of learning.

In the opening section of the article we gave an overview of the influence the *learning sciences* and *science studies* have had on extending our understandings of science learning, science practices, scientific knowledge, and scientific discourse. Cognitive, historical, sociological, and anthropological studies of individuals working in knowledge building contexts all emphasize the importance of the practices occurring in these communities. With respect to the scientific disciplines, cognitive models of science (Giere 1988; Goldman 1986; Kitcher 1993; Thagard 1992) coupled with sociocultural models of science (Knorr-Cetina 1999; Kuhn 1970; Longino 1990, 2002) have established the importance that models and modeling, visual representations, knowledge exchange mechanisms and peer interactions have in the advancement and refinement of knowledge. Doing science is situated in complex settings of cognitive, epistemic and social practices.

The view of science and science learning as fundamentally a model building and refining enterprise has gained traction. Models are seen as cognitive tools situated between experiments and theories (Giere 1988, 2002; Nersessian 2002, 2008a, b). As previously mentioned, the synthesis research report *Taking Science to School* (NRC 2007) recommends a shift in focus from science inquiry to scientific practices. This idea have been elaborated in the US National Research Council policy report *A Framework for K-12 Science Education* (NRC 2012) that is guiding the development of the *Next Generation Science Standards*. The *Framework* details how the teaching and learning of science should support learning progressions and be coordinated around eight Science and Engineering Practices, seven Cross Cutting Concepts and Disciplinary Core Ideas. The 3 Dimensions of Science Education are presented in Table 2.

This tripartite perspective on school science reflects a synthesis of ideas about the growth of knowledge and the nature of scientific reasoning taken from the learning sciences community and from the science studies community. This perspective also frames Version 2 for explicitly teaching the nature which we take up in the next section. Contemporary philosophical accounts of the growth of scientific knowledge [e.g., Knorr-Cetina's (1999) epistemic cultures] have adopted naturalistic accounts to explain the emergence of new conceptual (what we know), methodological (how we know), and epistemological (why we believe) criteria for the growth of scientific knowledge and the mechanisms of scientific reasoning. Grounded strongly in perspectives from philosophy of science, philosophy of mind, and developmental psychology, the interdisciplinary approach to understanding science has established firmly that learning, cognition and reasoning are contingent on context. We now turn to the debate regarding how best to present and represent the NOS in precollege science education.

5 Explicit NOS Instruction—Heuristic Principles Versus Model-Based Practices

Three issues arise when it comes to NOS instructional approaches (1) What is meant by 'explicitly' teaching NOS? (i.e., What is the substance of NOS?), (2) Should science inquiry and NOS be seen as coupled or as separate? and (3) How to assess learners' images of science? (i.e., What observations and measures provide reliable interpretations?) Below we present two competing perspectives and elaborate on how each of these three issues is addressed differently. Version 1 focuses on the use of heuristic principles and domain-general consensus-based statements taught in the context of lessons and activities. Version

Table 2 The three dimensions of the framework

1. Scientific and engineering practices	3. Disciplinary core ideas
1. Asking questions (for science) and defining problems (for engineering)	**Physical sciences**
2. Developing and using models	PS 1: Matter and its interactions
3. Planning and carrying out investigations	PS 2: Motion and stability: Forces and interactions
4. Analyzing and interpreting data	PS 3: Energy
5. Using mathematics and computational thinking	PS 4: Waves and their applications in technologies for information transfer
6. Constructing explanations (for science) and designing solutions (for engineering)	**Life sciences**
7. Engaging in argument from evidence	LS 1: From molecules to organisms structures and processes
8. Obtaining, evaluating and communicating information	LS 2: Ecosystems: Interactions, energy, and dynamics
2. Crosscutting concepts	LS 3: Heredity inheritance and variation of traits
1. Patterns	LS 4: Biological evolution Unity and diversity
2. Cause and effect mechanism and explanation	**Earth and Space Sciences**
3. Scale, proportion and quantity	ESS 1: Earth's place in the universe
4. Systems and system models	ESS 2: Earth's systems
5. Energy and matter: Flows cycles, and conservation	ESS 3: Earth and human activity
6. Structure and function	**Engineering technology and the applications of sciences**
7. Stability and change	ETS 1: Engineering design
	ETS 2: Links among Engineering technology, science, and society

NRC (2012) a framework for k-12 science education: crosscutting concepts, scientific practices and core ideas, executive summary

1 maintains that inquiry and NOS are separate. Version 2 focuses on scientific practices (See Table 2) in domain-specific contexts and advocates embedding students enactments of the practices over longer teaching sequences (e.g., immersion units and learning progressions) Version 2 sees inquiry and NOS as coupled.

5.1 Teaching NOS Explicitly—Version 1

5.1.1 Consensus Heuristic Principles and Science Lessons and Activities

Mansor Niaz's (2009) book *Critical appraisal of physical science as a human enterprise: Dynamics of scientific progress* serves as an example of the Version 1 perspective for teaching NOS. Grounded in Lakatosian views of philosophy of science, Niaz exemplifies how Version 1 science educators investigating the teaching of NOS have not moved beyond the historical-turn period in philosophy of science in their thinking. Niaz's book, like others advocating for Version 1, embraces a rational reconstruction view of scientific developments and the growth of knowledge. Niaz organizes his research agenda around Lakatos' notion of heuristic principles. For Niaz the consensus NOS statements listed below become the teachable moments in the examination of physical science historical episodes (e.g., Bending of Light in the 1919 Eclipse Experiment: Einstein and Eddington; Kinetic Theory: Maxwell's Presuppositions). At the end of each chapter Niaz discusses which of the eleven NOS heuristics can be addressed or demonstrated in studying this historical episode. As such, Niaz claims the interpretive components or heuristic principles of scientific knowledge can be used for documenting the growth of knowledge developments in the physical sciences and by extension can be used as frameworks for guiding science teaching about NOS

Niaz, like Abd-El-Khalick (2012) and Lederman et al. (2002) claim that despite the complexity of multifaceted NOS issues and the controversy among philosophers of science themselves "a certain degree of consensus has been achieved within the science education community [such that] the nature of science can be characterized, among others, by the following aspects" (Niaz 2009, p. 33):

1. Scientific knowledge relies heavily, but not entirely, on observations, experimental evidence, rational arguments, and skepticism.
2. Observations are theory-laden.
3. Science is tentative/fallible.
4. There is no one-way to do science and hence no universal, recipe-like, step-by-step scientific method can be found.
5. Laws and theories serve different roles in science and hence theories do not become laws even with additional evidence.
6. Scientific progress is characterized by competition among rival theories.
7. Different scientists can interpret the same experimental data in more than one way.
8. Development of scientific theories at times is based on inconsistent foundations.
9. Scientists require accurate record keeping, peer review, and replicability.
10. Scientists are creative and often resort to imagination and speculation.
11. Scientific ideas are affected by their social and historical culture.

These 11 statements are representative of statements from other consensus-list researchers (McComas and Olson 1998; Osborne et al. 2003, Lederman and Lederman 2004). Reading the 11 point list one can appreciate how we the authors along with other science education researchers and philosophers of science agree that most of these statements are accurate but are at odds with the lack of attention to cognitive, epistemic and methodological practices.

Eflin et al. (1999) have harshly critiqued NOS assessments based on consensus lists for confusing epistemological, ontological, and metaphysical features of science. Van Dijk (2011) raises concerns that unifying items ignore the heterogeneity of science and thus work against enhancing the public's functional scientific literacy. Cetin et al. (2010) and Rudolph (2000) find problems with the universalist consensus-based aspects not accurately depicting practices in science domains (e.g., chemistry). Wenning (2006) takes issue with instruments employing short response and survey formats that probe for students' perspectives rather than correct NOS points of views. Van Eijck et al. (2008) take issue with consensus lists when used as instructional practices that guide students' to learn particular images of science that are devoid of science practices. When the consensus lists are used to develop assessments as found in Lederman and Abd-El-Khalick (1998) and science lesson activities as found in Lederman and Lederman (2004) the domain-general consensus lists have been judged to represent distortions of historical depictions of science (Allchin 2011, 2012; Rudolph 2000; Matthews 2012), of publics understanding of science (Van Dijk 2011) and of contemporary scientific practices (Ault and Dodick 2010; Van Eick et al. 2008; Duschl and Grandy 2008).

Matthews (2012) presents a scholarly deconstruction of the 'Lederman Seven' consensus list and the accompanying ideas that NOS can be taught and learned through the completion of activities, the 'Lederman Programme'. The 'Lederman Seven' (Lederman et al. 2002) are:

1. Empirical nature of science.
2. Scientific theory and law.

3. Creative and imaginative nature of scientific knowledge.
4. Theory-laden nature of scientific knowledge.
5. Social and cultural embeddedness of scientific knowledge.
6. Myth of scientific method.
7. Tentative nature of science.

Matthews is most concerned with the omission of history of science in the teaching and learning of knowledge about science. But he is also concerned about the:

[P]hilosophical and educational pitfalls that have been associated with a good deal of recent NOS research:

1. The confused jumbling together of epistemological, sociological, psychological, ethical, commercial and philosophical features into a single NOS list.
2. The privileging of one side of what are contentious and much-debated arguments about the methodology or nature of science.
3. The assumption of particular solutions of the demarcation dispute.
4. The assumption that NOS learning can be judged and assessed by students' capacity to identify some number of declarative statements about NOS (Matthews 2012, p. 4).

Matthews suggests a change away from NOS consensus list items to the adoption of 'Features of Science' that are "more relaxed, contextual and heterogenous" (p. 3). The goal for Matthews is NOS elements that are more "philosophically and historically refined" (p. 11) so as to achieve philosophical articulation. Each of the 'Lederman Seven' is examined and critiqued by Matthews to demonstrate the complexities therein. Matthews' suggestion is to treat the seven items as features of science (1) Empirical basis; (2) Scientific theories and laws; (3) Creativity; (4) Theory dependence; (5) Cultural embeddedness; (6) Scientific method; (7) Tentativeness and to add the following three features (8) Experimentation; (9) Idealisation, (10) Models.

One major difference between Versions 1 and 2 proponents is whether enactments of students doing science though engagements with practices influence understandings about NOS. The joining of NOS and inquiry is contested by Version 1 advocates who embrace the 'degree of consensus' point-of-view for listing aspects of NOS and perceive 'doing science' as an obstacle to learning about NOS. Abd-El-Khalick (2012) concludes "equating NOS with scientific practice is an unfounded and unfruitful approach to teaching and learning about NOS in precollege classrooms." (p. 371) For Version 1 adherents, using episodes from history of science (Clough 2011; Niaz 2009) or lessons/activities that point out examples of consensus list aspects or heuristic principles is the way to explicitly teach NOS (Lederman and Abd-El-Khalick 1998). Niaz writes paraphrasing Lederman:

> A major difficulty in implementing NOS is the expectations that students will come to understand it by "doing science" (Lederman 2004, p. 315). This is like assuming that students would come to understand photosynthesis just by watching a plant grow. In order to facilitate understanding of NOS, teachers need to go beyond the traditional curriculum and emphasize the difficulties faced by the scientists, and how the interpretation of data is always problematic, leading to controversies among contending groups of researchers. (Niaz 2009, p. 24)

On the issue of separating inquiry from NOS, Schwartz et al. (2012) write the following in a commentary on Allchin's (2011) proposal to teach and assess NOS employing Whole Science case studies:

> The objectives Allchin targets are more aligned with inquiry and the nature of scientific inquiry (NOSI), rather than knowledge of NOS. We make a distinction between inquiry abilities, NOSI, and NOS in our work … whereas Allchin lumps all these constructs together into "doing NOS," thus

> minimizing the importance of understanding these concepts, constructions and their associated nuances and interrelationships. (Schwartz et al. 2012, p. 686).

Of course, the Version 1 position to dismiss science practices hinges on what is meant by 'doing science' and 'inquiry'. When the 'doing' is engaging in investigations within discrete single session lesson units and modules that are not sequenced around core ideas, then highlighting in texts or lessons where and when consensus list principles apply and align maybe appropriate. This approach would certainly seem to fit with existing modularized disconnected science education curricula that prevail in most schools at the moment.

However, the agenda for US science education has changed (NRC 2012) and it is one that is conceptualizing curriculum, instruction and assessment as integrated coherent teaching sequences, immersion units, and learning progressions. Additionally, the focus is on the 3 Dimensions Cross Cutting Concepts, Science Practices and Core Ideas. Doing science and using knowledge affords opportunities to enact an alternative version of explicitly teaching NOS. Table 3 summarizes what we conceive as the salient differences between Versions 1 and 2.

5.2 Teaching NOS Explicitly—Version 2

5.2.1 Scientific Practices and Whole Cases in Immersion Units and Learning Progressions

Version 2 embraces recommendations found in the NRC research synthesis reports that stress the importance of students using knowledge and participating in science practices.

Table 3 Explicit teaching distinctions Versions 1 and 2

Version 1	Version 2
Grounded in dated (logical positivism and historical turn) views that depict NOS through heuristics that focus on individual scientists justification of knowledge	Grounded in contemporary (naturalized philosophy of science) views that depict NOS through group activities that focus on cognitive, material, and mechanistic practices
Dominated by philosophical views based on physics	Inclusive of philosophical views from a range of science disciplines
Domain-general orientation of NOS—heuristics	Domain-specific orientation of NOS—disciplinary practices
Inquiry teaching in lessons and activities that demonstrate learners' consensus 'Features' of NOS	Learning/doing situated in longer instructional sequences that engage learners with scientific practices
Tactics and strategies of scientists less prevalent or missing	Tactics and strategies of scientists more prevalent or central
Core discourse practices of science missing—(e.g., measurement, representation, observation, and evaluating evidence/explanation)	Core discourse practices of science central—(e.g., talk/argument, models/representations; critique and communication)
Curriculum and instruction not aligned with assessment of learning formats	Curriculum and instruction aligned with assessment for learning formats
Theory and law approach	Model-based approach
Partitioning of philosophy, psychology and sociology. Ignores anthropology	Alignment of philosophy, psychology, sociology and anthropology
History of Science cases emblematic and episodic	History of science cases holistic and complex renditions

The focus on 'doing science' and using knowledge follows from cognitive science research recommendations reported in a series of NRC reports addressing learning, assessment, reading, mathematics education, science education, informal science education and STEM education, among others. The relevant reports here are *Taking Science to School: Learning and Teaching Science in Grades K-8* (NRC 2007), *Learning in Informal Environments* (NRC 2009), and *Knowing What Students Know* (NRC 2001).

Version 2 also embraces tenets from naturalized philosophy of science. Naturalized philosophy views NOS and scientific inquiry as continuous, not separate entities. This view of NOS focuses on the scientific practices embedded in the three statements below. As discussed earlier, many philosophers of science were taking the *historical turn,* other philosophers were engaging in the *naturalistic turn.* The *naturalistic turn* in philosophy of science was a response by philosophers to fill in the gaps left by the demolition by Kuhn and others of the basic tenets of logical positivism. The naturalized philosophy movement developed NOS perspectives that:

1. Emphasize the role of models and data construction in the scientific practices of theory development and refinement.
2. See the scientific community as an essential part of scientific practices, consequently emphasizing the practices of representation and argumentation.
3. See cognitive scientific practices as embedded in a distributed system that includes instruments, forms of representation, and agreed upon systems for communication and argument.

In Version 2 "explicit" does not refer to pointing out to students where the NOS features or heuristic principle are found in lessons and activities. Rather, explicit refers to students being immersed in the cognitive, epistemic and social enactments and practices of science that involve building and refining questions, measurements, representations, models and explanations. There is recognition and appreciation today, where previous reform efforts did not lacking knowledge from the learning sciences and science studies research, that we need to see science as involving (1) reasoning about evidence, (2) theory and model change, and (3) participation in the culture of scientific practices. Important dynamic elements of what it means to be doing science include:

- Building theories and models.
- Collecting and analyzing data from observations or experiments.
- Constructing arguments.
- Using specialized ways to talking, writing, and representing phenomenon.

One justification that is often given for the inclusion of NOS is that understanding how scientific knowledge is constructed makes one better at doing and learning science (Sandoval 2005). Sandoval reviewed the various consensus-list definitions of epistemology from Osborne et al. (2003), Lederman et al. (2002), McComas and Olson (1998) and proposed a more manageable list based on four broad epistemological themes:

1. Viewing science knowledge as constructed is important because it reinforces the dialectic practices between theory and evidence.
2. Recognizing that scientific methods are diverse, e.g., experiments are conducted in some fields and not in others. Rather than relying on method(s), science depends on ways of evaluating scientific claims.

3. Scientific knowledge comes in different forms that vary in explanatory and predictive power. An essential feature that is central to understanding the interactions of knowledge forms in inquiry.
4. Scientific knowledge varies in certainty and thus invites students to engage ideas critically and evaluate them with epistemological criteria.

We introduce here three research programs that exemplify and provide evidence for the value of Version 2 perspectives for teaching NOS. Each adopts measures that are not surveys of features of science but instead draw upon students' work samples and interviews couched in terms of Sandoval's epistemological themes. Research programs led by Kathleen Metz, by Carol Smith and by Richard Lehrer and Leona Schabule, provide evidence of how instruction-assisted development of scientific practices can enhance learner's understandings of NOS.

Metz (2008) reports on two curriculum-based studies with 1st graders, one in botany research on plant growth and one in animal behavior on crickets. The 1st grade students' engagements in knowledge-building practices are based on curricula scaffolded around 7 interrelated features that support engagement in science practices:

1. Immersion in strategically selected scientific domains;
2. Centrality of big ideas in the practices;
3. Entwining of content and process;
4. Centrality of curiosity as a drive for doing science;
5. Discovery and explanation as top level goals;
6. Challenge of making sense of the ill-structured; and
7. The social nature of scientific knowledge-building-practices.

The initial versions of the curricula demonstrated that children are capable of designing investigations and coping with uncertainty around researchable questions which were adapted and used successfully across several elementary grade levels (Metz 2004). Vignettes were used to capture students' meaning making and learning. For example, the 1st grade vignettes drawn from beginning, mid-point, and end of curriculum reports reveal how the deepening of students' knowledge supports thinking and contributes to increased accountability on the part of the students. Through this immersion experience children were being introduced to and provided opportunities to engage in evidence to theory scientific practices that shape perspectives regarding NOS.

Carol Smith has contributed many research studies (e.g., Cary and Smith 1993; Smith and Wenk 2006) on students' understandings of the NOS. Her research seeks to characterize students' epistemologies at 3 levels using the Nature of Science Interview protocol developed by Susan Carey (Carey and Smith 1993). The 'sets of questions' format of the interview appears in Appendix A. Each question is scored as Levels 1, 2 or 3. Students at Level 1 (Knowledge unproblematic epistemology) view scientific knowledge as a collection of true beliefs about how to do something correctly or as basic facts. Scientific knowledge accumulates piecemeal through telling and observation which is certain and true. At Level 2, science knowledge is seen as a set of tested ideas. Notions of explanation and testing hypotheses appear at this level. Here students view science as figuring out how and why things work and absolute knowledge comes about through diligence and effort. Level 2 is the transition between the epistemologies At Level 3 (Knowledge problematic epistemology) scientific knowledge consists of well-tested theories that are used to explain and predict natural events. "A theory is understood as a coherent, explanatory framework that consists of a network of hypothetical theoretical entities that are used to explain patterns of data." (Smith et al. 2000, p. 357) Theories are seen as guiding inquiry and evidence from experiments is not only view for/against hypotheses but theories as well. Theories are also seen as "more or less useful rather than strictly right or wrong" … [and] as that knowledge of reality is fundamentally elusive and uncertain." (p. 357)

One research study in particular (Smith et al. 2000) exemplifies the impact students' sustained engagement in thinking about epistemic issues can have on the progress elementary students can make in understanding the conjectural, explanatory, testable, and revisable nature of theories. Two demographically similar cohorts of 6th grade students were interviewed individually. Both groups experienced sustained science instruction one taught with constructivist methods and one taught with traditional methods. What is intriguing about this comparison study is that the 6th grade students in the constructivist classroom were with the same teacher for 6 years while students receiving traditional teaching had the same teacher for 5 years. The study serves as an exemplar of what can occur when coherent sustained science instruction that focuses on scientific practices takes place. The students in the constructivist science learning environment had understandings that went,

> well beyond what has been previously reported in the epistemological literature for students this age, and therefore provide further evidence against the view that there are biologically based developmental constraints on young children's thinking of the type envisioned by Piaget. Although their understanding fall short of a Level 3 epistemological stance, these students have made progress in appreciating some of the kinds of mental and social work that are part of the process of scientific knowledge acquisition. (Smith et al. 2000, p. 393)

Interested readers are strongly encouraged to go to the article for the robust reporting of study's rich details and findings.

The third research program that exemplifies Version 2 is that of Richard Lehrer and Leona Schauble who have pursued a program of research that examines the role of models and modeling in children's learning and teacher's instruction. For more than a decade they have examined elementary and middle school grade students' modeling of 'big ideas' that serve as a conceptual foundation to reasoning about the theory of evolution (Lehrer and Schauble 2012a, b). Their approach is to engage children in representation and modeling practices around three building block constructs for evolutionary thinking: Change, Variation and Ecosystems. The research agenda is to better understand the learning progressions that support the development of students' conceptual and epistemic learning. Thus, a related agenda is to understand the dynamics of instruction-assisted develop wherein teachers use formative assessments that make thinking visible to guide instruction and learning.

Lehrer and Schauble (2012b) is a conceptual report on the design features and structures that informed the development of a modeling learning progression. Lehrer and Schauble (2012a) and Lehrer et al. (2008) report classroom design research studies that tested conjectures about students learning that informed the development of the learning progression on evolutionary thinking. The design of instruction coordinated students' investigations of change and variation within different ecosystems and ecosystem frameworks. The ecosystems studied were local (e.g., school yards, river, pond, forest, prairie) and instruction was guided by the following generative principles that reveal the central role scientific practices play in instruction (Lehrer and Schauble 2012b):

- *Learning in Depth*—"[R]epeated investigations of the "same" ecosystem." "Develop basic familiarity with potentially important components of natural systems and with tools that can be used to investigate it." (pp. 716–717)

- *Posing Questions*—"[T]hat can be addressed via investigations … encourage revisions and generation of new questions by students over time." (p. 717)
- *Comparative Study*—"[S]tudents have the opportunity to learn by contrasting cases." (p. 717)
- *Arranging Conditions of Investigation*—"[S]tudents … 'getting a grip' on the material world to participate in the development of means to answer their inquiries." (p. 717)
- *Inventing Measures*—"We position students to invent measures and inscription and to coordinate these measures and representations as means for answering questions … aspects of scientific practice … often underemphasized in school science." (p. 719)
- *Inscribing and Representing Nature*—"Involves students both in closer examination of the natural systems they are seeking to depict and in thinking about the functions and uses of inscription." (p. 720)
- *Collective Participation*—"[S]tudents participate collectively, in a manner that makes the social side of scientific practice visible. The educational design should plan for situations that provide value added from the collective—forms of data sharing that allow better resolution of a questions, and/or spur new forms of investigation—and dialog that encourages student disposition to sustain investigation." (p. 721)

Lehrer and associates (2008) is a report of research on 5th and 6th grade students engagement in a year-long investigation of a pond ecosystem. This research study informed ideas about the importance of students' *Arranging Conditions for Investigations* and *Collective Participation*. Part of the instruction during the winter months had students design and build models of ponds in gallon jars. This provided a basis for studying the questions students had generated about pond ecosystems from outdoor excursions to a pond in the Fall months. Lehrer and colleagues found that unintended outcomes like algae blooms and bacteria colonies afforded opportunities to examine how ecosystems function. Subsequent efforts to model the pond ecologies were supported by weekly whole class research meetings. During these 'research meetings' students exchanged ideas and discussed relations between evidence and explanations. For example, the students struggled with the material design of the jar-ponds, and the ensuing dialogues were found to foster a pedagogy of inquiry. Lehrer and Schauble (2012b) commenting on the pond study found that when classroom conversations were directed to evidence there was a shift during the year from "evidence was believable if it came from trustworthy sources or direct experience [to] criteria that tied evidence to forms of data representation and culminated in the statement that evidence deserves to be valued to the extent that it is germane to the research questions being investigated, not simply a tour of whatever the investigator noticed." (p. 21)

From end of year interviews they found other interesting NOS outcomes (Lehrer et al. 2008). Interviews were conducted with students to assess understandings about ecology, understandings of research design and beliefs about an epistemology of inquiry. To elicit views about the nature of inquiry, interviewers asked students to compare and contrast the extended inquiry on ponds with kit-based science lessons the students had used. The researchers found that the weekly research meetings were a major influence on students' views about the nature of inquiry. They found that when instruction–assisted inquiry is sustained over longer periods of time, the absolutist views students are reported to have about the NOS and the absence of model-based views of science among learners go away. Also, students reported that the repeated efforts and struggles to make the jar-ponds work was preferred over the clearer outcomes found in kits. Such a finding has important implications for research on motivating students to engage in science and build identities in science (Blumenfeld et al. 2006). Another finding from the pond study—students developing model-based views of inquiry "in which collective practice and authority are intertwined with individual agency" (Lehrer et al. 2008, p. 17)—challenges current research findings on teaching and learning images about the nature of science.

A recommendation from the *Taking Science to School* (NRC 2007) research report is that Kindergarten to Grade 8 science instruction should be coordinated around these 'doing science' elements. Features of the Version 2 framing of explicit NOS instruction include seeing the nature of inquiry as seamless with NOS, not separating the teaching of concepts from engagements with scientific practices. Version 2 embraces an expanded scientific method (Duschl and Grandy 2008) that recognizes the role of experiment and hypothesis testing in scientific inquiry, but further emphasizes that the results of experiments are used in discourses that advance, build, compare, and refine models and theories. Thus, the expanded scientific method and Version 2 recognize that science involves important dialectical practices that function across conceptual, epistemic and social dimensions. One could argue that Conant's tactics and strategies focus has been revived but with a new domain-specific perspective on scientific practices as borne out of contemporary developments in philosophy of science and psychology.

6 Conclusions

"All those involved with science teaching and learning should have a common, accurate view of the nature of science." (NSTA 2000)

Our position is that the fundamental aspects of 'doing science' are using evidence to build theories, models, and mechanisms that explain natural systems, and to use those theories and models to devise experiments or observational studies that provide evidence. Laudan (1981) provides the following examples of scientific theories once believed to be true and then found otherwise:

- Catastrophist geology.
- The phlogiston theory of chemistry.
- The caloric theory of heat.
- The vital force theory of physiology.
- The ether theories of electromagnetism and optics.

Newton-Smith (1981) referred to this as "pessimistic induction" in that any scientific theory once believed to be true will eventually be found false. We see this in Version 1 statements such as 'Scientific knowledge is tentative.' So, we might ask what confidence can we have in scientific inquiry leading to scientific truths? As Thagard (2007) points out, "It is noteworthy that Laudan's examples are all from before the twentieth century, and one could argue that recent science has been more successful in achieving true theories" (p. 34). Much of this success and our confidence in science as a way of knowing can be explained by our developing understandings of the practices associated with the growth of scientific knowledge.

Thagard (2007) posits that coherence and explanatory coherence are achieved through the complementary process in which theories broaden and deepen over time by accounting for new facts and providing explanations of why the theory works. Our position is that the general features of theory articulation and refinement and theory broadening and deepening are the basis for both 'doing science' and 'learning science'. Throughout we have pointed to the NRC research summary report *Taking Science to School* (*TSTS*) (NRC 2007) that maintains the basis for a sound science education is dependent on learners' progress across four interwoven strands of proficiency:

1. Know, use, and interpret scientific explanation of the natural world.
2. Generate and evaluate scientific evidence and explanations.
3. Understand the nature and development of scientific knowledge.
4. Participate productively in scientific practices and discourse.

The message from the 4 strands view is that science education is more than teaching what we know. Science education is also and importantly about how we know and why we believe what we know over alternatives; e.g., the cognitive, epistemic, and social discourse practices that characterize science.

The above quote at the beginning of this section is from the *Preamble* to the current NSTA Position Statement on the Nature of Science. We have argued that the current state of affairs in NOS and science education that adopt Version 1 do not represent an accurate view of the nature of science. First, there is the exclusion of model-based practices that are inherent in *TSTS* Strand 3 of the science proficiencies "Understand the nature and development of scientific knowledge." Second, there is the omission of critique, communication and representation discourse practices that are the basis of *TSTS* Strand 4 "Participate productively in scientific practices and discourse." Third, new views of NOS stress the role of cognitive, epistemic, and social dynamics in the growth of scientific knowledge.

What the three research programs in the previous section demonstrate is that with the right context sustained for a longer period of time students can develop more sophisticated and nuanced views about the nature of science. New tools, technologies, techniques and cognate theories contribute to the progressive development of the scope of a theory; i.e., Thagard's deepening and broadening. The research by Metz, Smith and colleagues and by Lehrer and Schauble are examples of how children are able to participate in cognitive, epistemic, and social practices. Moreover, through such sustained dialogic processes learners' develop more sophisticated views about growth of scientific knowledge and thus NOS.

Whether or not we choose to capitalize on learner's emerging scientific reasoning abilities and further develop them depends on how we construe the goals of science learning and how such learning outcomes can be achieved. Versions 1 and 2 offer stark alternatives to teaching *about* science. We have argued that a focus on doing science and on how scientific knowledge is developed and evaluated will entail building on students' emerging capacities for representation, model-building, and casual reasoning.

If the focus of science education is on the accumulation of scientific facts and heuristic principles without using that information to propose explanations and predictions and to evaluate the growth of scientific knowledge, then it is not clear how one capitalizes on students emerging understandings about NOS. Thus, the NRC science education research and policy documents (NRC 2007, 2009) argue for a science education that focuses on the investigative and discourse practices embedded in model/theory building/refining; e.g., knowing and doing. Advances in our understandings about learning have occurred in tandem with our richer understandings about the growth of knowledge within STEM disciplines. Essentially, we are learning how to learn about the natural and designed world and about learning itself.

We have argued that ideas from interdisciplinary research communities labeled *learning sciences* and *science studies* are extending our understandings of science learning, science practices, scientific knowledge, and scientific discourse. Cognitive, historical, sociological, and anthropological studies of individuals and groups in knowledge building contexts reveal the importance of practices in these knowledge growth communities. With respect to the scientific disciplines, cognitive and sociocultural models of science have established the importance modeling, visual representations, knowledge exchange mechanisms and peer interactions have in the advancement and refinement of knowledge and in the growth of scientific knowledge. Such practices need to be a central component of K-16 STEM education and divorcing practices from NOS is seen as doing more harm than good. In brief, doing science takes place in complex settings of cognitive, epistemic and social practices. Our position is science learning environments should be designed and enacted around these same knowledge exchange and growth of knowledge practices. It's time once again to heed the sage advice of James Conant, knowledge *about* science should stress the tactics and strategies of scientists.

Appendix 1

See Table 4.

Table 4 NOS instruments

Title/author	Format/sample	Scales–categories	Representative items
Test on understanding science (TOUS) Cooley and Klopfer (1961)	60 multiple choice items 4 options secondary students	1. Understandings about scientists. 2. Understandings about scientific enterprise. 3. Understanding about the methods and aims of science	Which one of the following statements best describes the most important way that scientists contribute to our society? (a) They provide knowledge about nature. (b) They make improved products for better living. (c) They provide skilled services or advice to others. (d) They show us what to strive for.
Nature of science survey (NOSS) Kimball (1967–1968)	29 items, 3 point Likert Scale Science teachers and scientists	Curiosity; process; orientation; no one scientific method; values of science; human endeavor; dynamic; comprehensiveness and simplicity; tentativeness	Agree Disagree Neutral The most important scientific ideas have been the result of a systematic process of logical thought. While biologists use the deductive approach to a problem, physicists always work inductively
Nature of scientific knowledge survey (NSKS) Rubba and Anderson (1978)	48 items, 5 point Likert Scale Secondary students	Amoral creative developmental parsimonious unified testable	Strongly Agree-Agree-Neutral-Disagree-Strongly Disagree Scientific laws, theories, and concepts do not express creativity The laws, theories, and concepts of biology, chemistry, and physics are not linked Scientific knowledge is specific as opposed to comprehensive

Table 4 continued

Title/author	Format/sample	Scales–categories	Representative items
Conception of scientific theory test COST Cotham and Smith 1981	50 items, 4 point Likert Scale; 4 paragraph statements: Theory of atom; theory of evolution; theory of abiogenesis; plate tectonic theory	*Testing*—tentative versus conclusive *Ontological Implications*—instrumentalist versus realist *Generation*—inventive versus inductive *Theory Choice*—Subjective versus Objective	Plate tectonics is a new theory. Given enough time it's likely that enough evidence will be accumulated to prove it conclusively 1 Strongly agree; 2 Agree; 3 Disagree; 4 Strongly disagree Even though no one ever saw isthmian links, if there were enough evidence in support of them, we could claim that they actually existed 1 Strongly agree; 2 Agree; 3 Disagree; 4 Strongly disagree
Views of science and technology (VOST) Aikenhead and Ryan (1992)	114 MC item pool—A–I choices	*Definitions:* Science and technology *External Sociology of Science:* Influence of society on S/T; influence of S/T on society; influence of school science on society *Internal Sociology of Science:* Characteristics of scientists; social construction of scientific knowledge; social construction of technology *Epistemology:* Nature of Scientific Knowledge	*60211 the best scientists are always very open-minded, logical, unbiased and objective in their work. These personal characteristics are needed for doing the best science.* Your position, basically: (Please read from A to I, and then choose one.) (A) The best scientists display these characteristics otherwise science will suffer. (B) The best scientists display these characteristics because the more of these characteristics you have, the better you'll do at science. (C) These characteristics are not enough. The best scientists also need other personal traits such as imagination, intelligence and honesty. The best scientists do NOT necessarily display these personal characteristics: (D) Because the best scientists sometimes become so deeply involved, interested or trained in their field, that they can be closed-minded, biased, subjective and not always logical in their work. (E) Because it depends on the individual scientist. Some are always open-minded, objective, etc. in their work; while others can be come closed-minded, subjective, etc. in their work. (F) The *best* scientists do NOT display these personal characteristics *any more than* the average scientist. These characteristics are NOT necessary for doing good science. (G) I don't understand. (H) I don't know enough about this subject to make a choice. (I) None of these choices fits my basic viewpoint

Table 4 continued

Title/author	Format/sample	Scales–categories	Representative items
Views of nature of science (VNOS) Lederman et al. (2002)	10 open ended questions	Student views of NOS Social and cultural embeddedness of science Existence of a universal scientific method	After scientists have developed a scientific theory (e.g., atomic theory, evolution theory), does the theory ever change? If you believe that scientific theories do not change, explain why. Defend your answer with examples. If you believe that scientific theories do change: (a) Explain why theories change? (b) Explain why we bother to learn scientific theories? Defend your answer with examples. Some claim that science is infused with social and cultural values. Others claim science is universal. If you believe that science reflects social and cultural values, explain why. Defend your answer with examples. If you believe science is universal, explain why. Defend your answer with examples
Nature of science interview Carey and Smith (1993)	23 questions with 4 level coding guide Elementary—middle school students	Goals of science (4) Types of questions (3) Nature and purpose of Experiments (3) Role of ideas: Conceptions of hypotheses and theories (6) Unexpected results and disproving ideas (2) Nature of change processes (3) Achieving goals and making mistakes (2)	*Nature and purpose of experiments* What is an experiment? Do scientists do experiments? Why do scientists do experiments? IF "to test ideas," THEN: How does the test tell the scientist something about the idea? *Nature of change processes* What happens to scientists' ideas once they have done a test? Do scientists ever change their ideas? *Achieving goals and making mistakes* Do scientists always achieve their goals? If not, why not? Can scientists make mistakes or be wrong? How?
Nature of science literacy test (NOSLiT) Wenning (2006)	35 multiple choice items high school students	None given	Well established scientific conclusions will generally remain unchanged with the passage of time, but are subject to change in the light of new evidence. This statement is ____, because ____. (a) True—scientific conclusions might change when new contradictory evidence is found. b) True—science is composed of theories that have a high probability of being wrong. c) False—once scientists make scientific conclusions, these conclusions can and will never change in the future because laws of the universe are always and everywhere the same. (d) False—science is the search for truth, and truth never changes

Appendix 2

See Table 5.

Table 5 NSTA policy statements

Position statement	Nature of science	Nature of inquiry	Image of child development
On science curriculum development (1964)	"Science is a systematic and connected arrangement of knowledge within a logical structure of theory. Science is also a *process* of forming such a structure"	"Learning from work in a laboratory and field is central to the teaching of science. It is here that the student relates concepts, theories, experiments and observations as a means of exploring ideas. While technical skills and precision are important outcomes of the laboratory, it is the meaning they have for the interpretation of data that is most significant"	"The elementary and secondary school science program should be planned to include all students. No fundamental differences in objective should exist for various student groups, although pace of instructive and illustrative examples might differ for "slower" and "accelerated" groups. "
Revision of position on curriculum development (1971)	"Science, because it is a human undertaking, cannot be value free … The following values underlie science: longing to know and understand, questioning of all things, search for data and their meaning, demand for verification, respect for logic, consideration of premises and consequences"	To create a scientifically literate citizenry "direct experiences with the natural world or in the laboratory should comprise the major portion of the science program" and "textbooks should facilitate inquiry, rather than being written to replace the laboratory experiences"	Objectives for any science program and the selection of material to be taught should be consistent with the "nature of the learner"
Science activities are central to science education in the elementary school (1981)	"Exploring nature and trying to understand its meaning is what science is about"	"To the science teacher, laboratory experiences provide a model of scientific investigation. Students begin with simple questions and work towards answers"	"Hands-on lab experiences which emphasize the process skills observing measuring, recording, classifying, interpreting data, inferring, predicting, investigating and making models can provide an important vehicle for the child's intellectual transition from concrete to abstract"
The laboratory is vital in science instruction in the secondary school (1982)	"The true meaning of science lies not in its products but in the unending 'quest for truth,' in which the validity and usefulness of established concepts is constantly challenged by new ideas"	"The laboratory gives the students firsthand experience with inquiry, the search for order and meaning in the natural environment"	"… different students possess reasoning patterns at various levels of sophistication. Therefore, it is important to examine the effects of different kinds of laboratories on groups of students with different kinds of reasoning patterns."

Table 5 continued

Position statement	Nature of science	Nature of inquiry	Image of child development
The National Science Education Standards: A vision for the improvement of science teaching and learning (1998)	"Subject matter stress should be on in-depth understanding of unifying concepts, principles, and themes …"	"Inquiry should be viewed as an instructional outcome (knowing and doing) for students to achieve …"	"Science programs should provide equitable opportunities for all students and should be developmental appropriate, interesting and relevant to students …"
The nature of science (current position) (2000)	"The scientific questions asked, the observations made, and the conclusions in science are to some extent influenced by the existing state of scientific knowledge, the social and cultural context of the researcher and the observer's experiences and expectations"	"Although no single universal step-by-step scientific method captures the complexity of doing science, a number of shared values and perspectives characterize a scientific approach to understanding nature. Among these are a demand for naturalistic explanations supported by empirical evidence that are, at least in principle, testable against the natural world"	
Scientific inquiry (current position) (2004)	"Science involves asking questions about the world and then developing scientific investigations to answers their questions"	Definition of inquiry adopted from the National Science Education Standards: "the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Scientific inquiry also refers to the activities through which students develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world"	

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