Naturalizing the Nature of Science:
Melding Minds, Models, and Mechanisms[1]

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Abstract

Our focus in this paper is on the effects that dated ideas, images, and principles about the nature of science (NOS) have on the design of curriculum standards and assessments and, thus on learners' and publics' images and characterizations of science. First we examine developments in teaching about NOS beginning with the seminal ideas of James Conant. Next we elaborate on developments in philosophy epistemology and cognitive science that have moved the field (1) to naturalized philosophy of science perspectives and (2) to a reconsideration of demarcation claims that distinguish science from non-science. We then turn to a discussion about NOS consensus models that are being used for teaching NOS in pre-college programs. We consider two competing views regarding 'explicitly teaching' NOS in pre-college programs: Version 1 - *Consensus Heuristic Principles in Historical Cases and Science Lessons and Activities* and Version 2 - *Scientific Practices and Whole Cases in Immersion Units & Learning Progressions.* Our position supports Version 2 on the basis that the refinement practices as found in tools, technology, technique, and theory choice is often ignored in science education. The middle ground refinements and debates between initial discovery and subsequent justifications constitute important elements of an enhanced view of teaching science as inquiry. Version 2 recognizes, where Version 1 does not, the critical epistemic frameworks and the dynamic cognitive and social practices that are used when developing and evaluating scientific knowledge or critiquing and communicating scientific ideas and information.

Introduction

Developments among philosophy, epistemology and cognitive science scholars examining the growth of scientific knowledge have led to the emergence of a naturalized philosophy of science. The general trajectory of philosophy of science during the 20th century has been away from a formal deductive-nomological orientation organized around language, logical practices and demarcation criteria toward the naturalized philosophy of science where the cognitive practices are embedded in social and epistemological practices. The influential transitional period between these philosophical endpoints was marked by the historical-turn theory-reconstruction period. To complicate matters even more, some features of the first two periods are retained in the naturalized

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philosophy of science. Our concern in this paper, as it pertains to organizing precollege science education programs, is the effect the continued inclusion of dated ideas, images, and principles about the nature of science has on the design of curriculum standards and assessments and, thus on learners' and publics' images and characterizations of science.

In matters of science education, especially teaching about the nature of science (NOS), it matters greatly which characterization(s) of science is adopted. Commitments to one of the competing views influence how science as a way of knowing is represented and which scientific practices are included and excluded. The paper begins by examining recent developments in teaching about the nature of science. We then elaborate on 20th century developments in philosophy of science that have moved the field to naturalized philosophy of science perspectives and to a reconsideration of demarcation claims that distinguish science from non-science. Next, we address concerns that extant NOS consensus models used for teaching the nature of science in pre-college programs do not accurately reflect naturalized epistemology or naturalized philosophy of science. More specifically, we will consider (1) two competing views regarding 'explicitly teaching' NOS in pre-college programs and (2) the 'demarcation' problem for distinguishing scientific reasoning and practices from other ways of knowing.

NOS and Science Education

When and how did images about the nature of science become a targeted curriculum topic and a focused learning goal in K-16 science education? From a US perspective, the decade of interest is the 1950s when two major post-war developments in science education policy initiatives occurred. One, in post secondary education, was the GI Bill that enabled military veterans to pursue university studies. The other, in secondary education, was the creation of the National Science Foundation that shifted teacher science education from industry (e.g., General Electric, Westinghouse) supported programs to broader peer reviewed federally funded science and mathematics curriculum development programs impacting both teachers and students.

NOS Development in Post-secondary Education

The catalyst in post-secondary education was Harvard University and Harvard 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, Leo Klopfer, Wayne Welch and Glen Aikenhead, among others, were at Harvard between 1955 and 1965 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* undergraduate curriculum set the tone and the vision for other Harvard-based science education reform efforts. 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.* Also noteworthy was the development of *Harvard Project Physics* high school curriculum.

Harvard Case Studies in Science and *Harvard Project Physics* adopted an historical approach to offer science to non-majors. Both projects were based on ideas put forth by James Conant. Conant's *On Understanding Science: A Historical Approach* (1947) set out an agenda and the rationale for a science course that would focus on knowledge about science as opposed to scientific knowledge. Anticipating changes to society that science, engineering and technology would make in the decades to come, 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 use a few 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. For Conant, it was important to understand the distinctions between research in pure and applied sciences and whether social sciences counted as 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)

There was skepticism on Conant's part that recent philosophical analysis had led to an accurate understanding of science. He was writing at a time when the Logical Positivism agenda of examining science through the lens of formal logic held sway and he comments critically on this agenda in *On Understanding Science.* To present the tactics and strategies of science he 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 – 17^{th} & 18^{th} Centuries
- Chemistry – 18^{th} & 19^{th} Centuries
- Geology – early 19^{th} Centuries
- Biology – 18^{th} & 19^{th} Centuries (certain phases)

The criteria for case selection were:

1) Progress has 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 & 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 & industry, e.g., agriculture, medicine.

Conant's other education and science education policy books focused on the structure of secondary education, which led to the development of ideas, and subsequently practices, regarding the comprehensive high school and the importance of science and mathematics as core subjects.

NOS Development in Secondary Education

The catalyst for rapidly changing the face of K-12 science education was the launching in 1957 of Sputnik, the USSR satellite. 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- high school 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, 2008), *The History of Science Education* (DeBore, 1991), and *Restructuring Science Education: The Role of Theories and Their Importance* (Duschl, 1990).

The inclusion of nature of science as a secondary education-learning goal, not surprisingly came from Harvard, too. Toward the end of the 1950s Leo Klopfer adapts the *Cases* for use in high schools (Klopfer & Cooley, 1963) and participates in developing the first instrument for assessing understandings about science - Test on Understanding Science (TOUS) (Cooley & 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. A comprehensive review of these NOS instruments can be found in Lederman (1995). In the US, a watershed event for changes in science education was 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. A review of the various NOS measures reveals that a common denominator of the research and development was establishing a set of topics, themes, or views that would inform and guide the assessment of student learning and the design of curricula.

What is important is to recognize the wide diversity that exists among the NOS measures that reflect the evolution of thinking in philosophy of science and in learning theory. A nice proxy for capturing these changes is to consider the 40-year evolution of NSTA Position Statements on Nature of Science, Nature of Inquiry and Images of Child Development presented in Figure 1.

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The changes in NSTA statements demonstrate that NOS views have moved to consider Kuhn's inspired 'historical turn' and the dynamics of theory change in science. What is not revealed from the NSTA statements is the concomitant critiques and comments from contemporary philosophers like Imre Lakatos and Larry Laudan who sought to rebuff the challenges Kuhn's paradigm shifts made on rational pathways for the growth of scientific knowledge. Heuristic principles, progressive and degenerative research programmes, positive and negative research traditions were added to the lexicon of philosophy of science to describe and account for changes and for growth in scientific knowledge. It can be argued that the transition to, but not the idea of, naturalized philosophy of science began with Kuhn's response to his critics that appears in the postscript of the 2nd edition of *Structures* (1970). Here Kuhn introduces the concept of the disciplinary matrix as a context to account for belief and theory changes in the sciences. Here Kuhn reinforces the roles of models and research communities.

Demarcation and the Path to Naturalized Philosophy of Science

The parade of science 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. Advances in science over the centuries have spawned multiple philosophical perspectives to account for the thinking and growth of knowledge. Over the last 100 years there are three major periods in philosophy of science:

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.

Across these three periods we identify 8 chronological events that moved the philosophical conversations forward:

1. The failure of formal inductive methods to provide an account of confirmation or explanation, and to set demarcation conditions

2. Emergence of the Social Pragmatic View of Language via accounts of the 'Causal Theory of Reference'

3. Emergence of Cognitive Psychologies as the dominance of Behaviorism recedes leading to research on cognitive processes such as reasoning and memory.
4. Emergence of Philosophy of Biology to introduce evolutionary ideas about emergence and the treatment of anomalous data.
5. Emergence of History of Science and the subsequent shift from accounts of older history to accounts of newer or contemporary history to establish growth of knowledge mechanisms.
6. Emergence of 'Practices' and Epistemic Cultures – cognitive and social – as a basis for interpreting the building and refining of scientific knowledge and methods.
7. Complex Systems Science (Discovery Science) and emergence.

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 20th 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 a 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 not predominantly the context of discovery or 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.

One way to argue for demarcation is to claim scientific inquiry involves mechanistic explanations. This is clearly too narrow as magnetism and gravitation are not mechanical. Another is to argue that scientific explanations are causal. This suggestion has two problems; one is that it seems to rule out statistical explanations that are not necessarily causal. The second is that three centuries of debate over the nature of causation in philosophy have produced no consensus on what constitutes causation.

Another view is that scientific explanations/hypotheses must be testable. While this seems right in spirit, decades of attempts by philosophers to make this concept precise have also consistently failed. Yet another tack is to argue that the distinction between scientific and non-scientific hypotheses is real, but is not a matter for which we can formulate explicit rules for general application, e.g., a Scientific Method. The only individuals able to appropriately make the distinction between testable and non-testable hypotheses are those who are deeply embedded in the practices of the specific science and have sophisticated knowledge. Today with the aid of powerful computers there are domains of science that do not begin inquiry with stating hypotheses but rather are guided by patterns of discovery from huge data sets (e.g., astronomy, human genome project).

We are not suggesting that it is impossible to distinguish scientific inquiry from pseudo-science. But we believe that to the extent that the distinction can be made, it has to be made locally, from the perspective of the particular field at a specific time. A naturalized approach to understanding science means that researchers observe what scientists do, not just what scientists say about what they do. The naturalized approach to the history of science strongly suggests that the nature of scientific activities has changed over time and we expect change to continue. Knowledge of the relevant scientific principles and criteria for what counts as an observation are important elements in distinguishing science claims and developing demarcation capacities; e.g., distinguishing science from pseudoscience. However, we are skeptical that a general demarcation criterion can be abstracted from the concrete historically situated judgments. And yet, in the context of creationism and evolution there is a desire to claim a demarcation on the grounds that the core theoretical belief system of one is religious and of the other is scientific. An alternative approach is to examine the scientific practices within a community of scientists, specifically, those scientific practices that as Thagard (2007) posits serve to broaden and deepen explanatory truths.

The Naturalistic Turn in Philosophy of Science

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 (Duschl, 2008; Duschl & Grandy, 2008). Consider the following core questions posed by Carruthers, Stich, and Siegal (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. 1).

Cognitive, historical, sociological, and anthropological studies of individuals working in knowledge building contexts reveals 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 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. These activities and practices progress from experiments on to models and then to explanatory theories.
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, 2008). 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 which we take up in the next section.

Our deeper understanding of how children's thinking reveals it is fundamentally different from that of adults and that "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)

During the *historical turn* of philosophy of science that began with the work of Kuhn (1970), Feyerabend (1975), and Lakatos (1970) a concurrent development in philosophy was the *naturalistic turn*. 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.

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)

Grounded strongly in perspectives from philosophy of science, philosophy of mind, and developmental psychology, the interdisciplinary approach to understanding science learning, knowing, and doing has established firmly that learning, cognition and reasoning are contingent on context as well as content. Twentieth century interdisciplinary efforts in understanding science and science learning contributed to developments in both our understandings of teaching and learning science and our understandings of how science works. Questions about 'How Science Works and How to Teach It?' would obviously have different answers depending on the perspectives one holds in Conant's terms about the tactics and strategies of science. We now turn to a debate regarding how to teach the nature of science. In the next section, two different versions for conceptualizing 'Explicitly Teaching NOS ' are examined.

Explicit NOS Instruction – Heuristic Principles vs. Model-based Processes

Any characterization of scientific inquiry raises the question of whether science as a way of knowing is distinctive. Philosophers of science refer to this as the *demarcation* issue (Eflin, Glennan & Reisch, 1999). Actually, there are two related but distinct demarcation questions. First, some individuals see a distinction between legitimate science and activities that purport to be scientific not only fail to be science but produce no knowledge at all, e.g., astrology, creation science, etc. Second, there are some who see a distinction between scientific inquiry and other forms of legitimate but non-scientific activities such as historical research or electrical engineering. Many advocates of teaching NOS in science education programs feel that it not only is possible to make a sharp general demarcation, but that it is important for students to understand the demarcation. (Lederman, Abd-el-Khalick, Bell, & Schwartz, 2002; McComas & Olson, 1998; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003) Others, as outlined above, are skeptical that such a demarcation is possible.

Niaz claims 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 [that] the nature of science can be characterized, among others, by the following aspects:

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." (Niaz, 2009; pp 33)

Niaz goes on to state that reviews of teachers' knowledge about these different NOS aspects indicates a majority of teachers lack understanding for some or all of the eleven consensus statements. Reading this list one can appreciate how we and other philosophers of science would be at odds with many of the statements (c.f., Eflin, Glennan & Reisch, 1999). When used to develop assessments (Lederman & Abd-El-Khalick , 2002) and activities (Lederman & Lederman, 2004) the consensus lists represent in many respects a distortion of both historical (Allchin, 2010) and contemporary scientific practices. (Van Dijk, 2011; Ault & Dodick, 2010; Duschl & Grandy, 2008)

When it comes to instructional approaches two issues that arise concern (1) what we mean by 'explicitly' teaching NOS and (2) whether science inquiry and NOS are coupled or not. The next sections present two competing perspectives. Version 1 focuses on the use of heuristic principles and consensus statements taught in the context of lessons and activities with inquiry and NOS uncoupled. Version 2 focuses on the use of scientific practices and whole historical cases taught in the context of longer teaching sequences (e.g., immersion units and learning progressions) with inquiry and NOS coupled.

Teaching NOS Explicitly – Version 1
Consensus Heuristic Principles in Historical Cases and Science Lessons and Activities

Two recent books linking science education to Lakatosian views of philosophy of science exemplify how science education thinking has not moved beyond the historical turn period in philosophy of science.

- Keith Taber's *Progressing Science Education: Constructing the Scientific Research Programme into the Contingent Nature of Learning Science*
- Mansor Niaz's *Critical appraisal of physical science as a human enterprise: Dynamics of scientific progress.*

The Taber and Niaz books represent a rational reconstruction of scientific developments and the growth of knowledge as, too, does Version 1. Taber acknowledges early in his book a debt to Imre Lakatos in thinking about how research within a domain is undertaken. Hence, we find in the book's chapter organization and content a strong commitment to Lakatos' heuristic guidance (The Negative Heuristic; The Protective Belt; The Positive Heuristic, Hard Core Axioms) as a "means of demarcation, a way of distinguishing the issues and questions that are on and off limits within the RP (Research Programme)". (p. 1) The RP under scrutiny for Taber is science learning functioning within the conceptual change constructivism framework.

Niaz also organizes his research agenda around Lakatos' heuristic principles. For Niaz the consensus NOS statements listed above 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 presents textbook analysis research results and then 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. Where problems begin is the extension of the growth of knowledge and the heuristic principles as frameworks for guiding science teaching about NOS.

Tabar employs heuristic principles for characterizing a research programme on the growth of knowledge in learners. Niaz, uses heuristic principles to characterize interpretive practices among scientists. In each case, there is a cursory and at times short treatment of ideas; heuristic principles can only do so much for characterizing NOS. Further, the omission of any discussions about important competing ideas and perspectives about science learning for Tabar and the growth of science knowledge for Niaz reinforce rational reconstruction and demarcation images. When accounts of science or representation of NOS are committed to heuristic principles for framing instruction the natural progressions of the growth of scientific knowledge that is found to occur among scientists are missing.

As mentioned previously, at the same time some philosophers of science were taking the *historical turn,* many philosophers were engaging in the *naturalistic turn.* The *naturalistic turn* in philosophy of science can be seen as filling in some of the gaps left by Kuhn's demolition of some of the basic tenets of logical positivism. The naturalized philosophy movement:

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

Naturalized philosophy, as supported by some science studies and science education researchers, (c.f., edited volumes by Carruthers, et al, 2002 and Duschl & Grandy, 2008) views NOS and scientific inquiry as continuous, not separate entities. This view of NOS focuses on the scientific practices embedded in the three preceding statements with inquiry representing an important diverse set of scientific practices. However, 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. For them, reviewing episodes of history of science or locating in lessons and activities and pointing out examples of consensus list heuristic principles is the way to explicitly teach NOS. Niaz writes:

> 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. (p. 24)

Of course, the Version 1 position hinges on what is meant by 'doing science'. When the 'doing' is engaging in investigations within discrete lesson units not sequenced around core ideas, then highlighting in texts or lessons where and when consensus list heuristic principles apply and align maybe the way to go. This approach would certainly seem to fit with existing modularized disconnected science education curricula that prevail in most schools at the moment. In contrast, conceptualizing curriculum around integrated teaching sequences, immersion units, and learning progressions, affords opportunities to embrace an alternative version of explicitly teaching NOS.

Teaching NOS Explicitly – Version 2
Scientific Practices and Whole Cases in Immersion Units & Learning Progressions

The past four decades have been a time of profound advances in our understanding about how people learn. Recent US National Research Council (NRC) synthesis research reports have targeted 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* (Duschl, Schweingruber & Shouse, 2007), *Learning in Informal Environments* (Bell, Lewenstein, Shouse & Feder, 2009), and *Knowing What Students Know* (Pellegrino, Chudowsky, & Glaser, 2001). The reports tell us that we have underestimated the capacity for children's science learning. The reports also tell us about the importance of instruction-assisted development coupled with targeted formative assessments in monitoring and advancing children's learning. Opportunities for using knowledge situated in or coordinate around scientific practices enhances motivation and understanding. Sequence and coherence of curriculum topics and instruction is important; longer teaching sequences and learning progressions are needed to develop reasoning and complex thinking. Students are capable of participating in science discourses that make thinking visible through argument, modeling and representations.

Version 2 embraces and reflects the tenets found in the NRC research synthesis reports. Here "explicit" does not refer to teachers pointing out for students the heuristic principle found in lessons and activities. Rather, explicit refers to students being immersed in the enactments and practices of science that involve building and refining questions, measurements, representations, models and explanations. 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, and developing learners' epistemic thinking capacities to both critique and communicate scientific ideas. Version 2 embraces an expanded scientific method that recognizes the role of experiment and hypothesis testing in scientific inquiry, but further emphasizes that the results of experiments are used to 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. In a sense, one could argue that Conant's tactics and strategies focus has been revived but with a new perspective on scientific practices.

Two research projects, one by Kathleen Metz and one by Richard Lehrer and Leona Schabule, provide insights into how instruction-assisted development can inform adaptive instruction strategies that enhance learner's understandings of scientific practices. 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.

Note that features 1, 5 and 7 embrace naturalized philosophy of science views. The initial versions of the curricula demonstrated that children can design investigations around researchable questions and cope with uncertainty; they were designed and used successfully across several elementary grade levels (Metz, 2004). The 1st grade vignettes draw from beginning, mid-point, and end of curriculum reports on the ways the deepening of knowledge supports thinking and contributes to increased accountability. Through an immersion experience children were being introduced to and provided opportunities to engage in scientific practices that shape perspectives regarding NOS.

Lehrer, Schauble, and Lucas (2008) engaged 6th grade students in year long pond studies. Part of the instruction had students design and build models of ponds in gallon jars. This provided a basis for studying questions the students had about the ponds. Lehrer et al. report 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 research meetings. During weekly '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 ensuring dialogues fostered pedagogy of inquiry.

End of year interviews with students assessed understandings about ecology and research design and beliefs about epistemology of inquiry. To elicit views about the nature of inquiry, interviewers asked students to contrast the extended inquiry on ponds with kit-based science. The researchers found that the weekly research meetings were a major influence on students' views about the nature of inquiry. 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" (p. 17) —challenges current research findings on teaching and learning images about the nature of science. Namely, when instruction –assisted inquiry is sustained over longer periods of time the absolutist views (Driver, Leach, Millar, & Scott, 1995; Lederman, 1992) students have about the NOS and the absence of model-based views of science among learners dissipate. With the right context students can develop more sophisticated naturalized views about the nature of science.

By way of comparison, if one were to generate a list of NOS features under Version 2, the target NOS understandings might include age appropriate versions of the following statements:

- The bulk of scientific efforts are not about theory discovery or theory testing but mostly theory improvement and refinement.
- Research groups and disciplinary communities, not individual scientists, are the units of practice for doing science.
- Scientific inquiry involves a complex set of discourse processes – talk, argument, models and representations.
- How science is done varies. The discourse practices of science are organized around disciplinary domains that share exemplars for making decisions regarding the values, instruments, methods, models, and evidence to adopt and use.
- Scientific inquiry has epistemic and social characteristics that occur in conceptual contexts.
- Changes in scientific knowledge are not just in conceptual understandings alone; important insights and advancements in science result from technological and methodological changes for conducting observations, making measurements and analyzing data.
- Theory and model choices influence 'what count' decisions and are an important dynamic in scientific inquiry.

Conclusion

When Darwin's dangerous idea was first introduced his arguments in *The Origin of Species* regarding the mechanism of natural selection changed forever the relationship between science and religion, man and nature and our interpretation of natural laws. In Kuhnian terminology, a scientific revolution had begun. Darwin's *The Descent of Man* only served to deepen the debate and widen the gulf between religious and scientific perspectives about the nature of science. The Great Synthesis in Biology introduced mechanisms to explain both the diversity of life and inherited stability of life. Molecular biology and population biology further deepened our understanding of the cellular and organism level mechanisms that account for evolutionary and co-evolutionary dynamics. Such fine-tuning of the understanding of evolution theory, or any scientific theory for that matter, is a critically important component in the growth of scientific knowledge.

New tools, technologies, techniques and cognate theories contribute to the progressive development of the scope of a theory. The research by Metz and by Lehrer and Schauble are examples of how children can participate in such cognitive and epistemic practices. However, the dialogical processes that take place between discovery and justification and that constitute the refinement of tool, technology, technique and theory choice, is an often ignored in science classrooms and communications. Such dialogic processes though are critically important dynamics of the growth of scientific knowledge and thus NOS features. The refinements and debates that are required between discovery and justification are as fundamental as observation and experiment. They should constitute elements of an enhanced view for explicitly teaching NOS. Such a view recognizes, where Version 1 views do not, the critical epistemic frameworks used when developing and evaluating scientific knowledge, as well as, the dynamic social processes and contexts for the critique and communication of scientific ideas and information.

The extensive research on infants and young children's cognitive development underscores the multitude of knowledge resources and reasoning capabilities children bring to formal schooling. Young learners are anything but empty minds. They are, when provided effective instructional conditions (Lehrer & Schauble, 2002), capable of noticing patterns and attributes in the natural world, linking the patterns and attributes to science concepts, developing explanations of natural phenomena, and reasoning about abstract ideas in meaningful and productive ways.

Whether or not we chose 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 understanding the doing of science and how scientific knowledge is developed and evaluated will entail building on students' emerging capacities for representation, model-building, casual reasoning. Three critical aspects of the nature of contexts and situations that are embedded in most views and research on learning within domain specific contexts are issues of *authenticity, collaboration* and *inquiry* (Blumenfeld et al., 2006). Authenticity, within the context of learning, focuses on embedding the learning within the natural phenomenon that are a part of learners' everyday world and the practices of the discipline. Collaboration encourages the sharing and contrasting of ideas with other individuals within a community who are engaged in similar tasks and share similar aims. Finally, inquiry motivates learners to engage in problem stating and solving activities, which require planning, synthesis and evaluation skills using relevant domain specific content knowledge.

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, then it is not clear how one might capitalize on the emerging understandings. Thus, the NRC research and policy documents (Duschl, et. al., 2007; Bell, et. al. 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. Research informs us that implementing such a building and refining learning environment allows students to bring significant conceptual resources that should be used as leverage for developing more sophisticated understandings of the scientific and engineering enterprises throughout schooling.

Advances in our understandings about learning have occurred in tandem with our richer understandings about the growth of knowledge within STEM disciplines – e.g., naturalized philosophy of science. Essentially, we are learning how to learn with respect to the natural and designed world and to learning itself. Thus, an important NOS feature is that scientific communities are responsive to new evidence, a more accurate depiction of the growth of scientific knowledge that the phrase ‘scientific knowledge is tentative’. 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 (Duschl, 2008; Duschl & Grandy, 2008). 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 and sociocultural models of science have established the importance of 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. In brief, doing science takes place in complex settings of cognitive, epistemic and social practices. Our science learning environments should be designed and enacted around these same knowledge exchange and growth of knowledge practices.

References

Ackerman, R.J. (1985). *Data, instruments, and theory: A dialectical approach to understanding science*. Princeton, NJ: Princeton University Press.

Allchin, D. (2011). Evaluating knowledge of the nature of (whole) science. *Science Education,* 95*(3).*

Ault, C. & Dodick, J. (2010). Tracking the Footprints Puzzle: The problematic persistence of science-as-process in teaching the nature and culture of science. *Science Education, 94*(6), 1092-1122.

Bell, P., Lewinstein, B, Shouse, A. & Feder, M. (2009). *Learning Science in Informal Environments: People, Places, and Pursuits.* Washington, DC: National Academy Press. (http://www.nap.edu).

Carruthers, P., Stich, S. & Siegal, M. Eds. (2002). *The cognitive basis of science.* Cambridge, UK: Cambridge University Press.

Conant, J. (1947). *On understanding science: A historical approach.* Cambridge, MA: Harvard University Press.

Cooley, W. & Klopfer, L. (1961). *Test on Understanding Science*. Princeton, NJ: Educational Testing Service.

Cooley, W. & Klopfer, L. (1963). The evaluation of specific educational innovations. *Journal of Research in Science Teaching*, *1*(1), 73-80.

DeBore, G. (1991) *The history of ideas in science education: Implications for practice*. New York: Teachers College Press.

Duschl, R. (in press). Keith S. Taber: Progressing Science Education: Constructing the Scientific Research Programme into the Contingent Nature of Learning Science. Science & Education.

Duschl, R. (2011). 'Critical appraisal of physical science as a human enterprise: dynamics of scientific progress', *Studies in Science Education*, *47*: 1, 103 — 107

Duschl, R. (2008). Science education in 3-part harmony: Balancing conceptual, epistemic and social learning goals. In. J. Green, A. Luke, & G. Kelly, Eds., *Review of Research in Education, V32.* (pp. 268-291) Washington, DC: AERA.

Duschl, R, Schweingruber, H. & Shouse, A. (2007). *Taking Science to School: Learning and Teaching Science Kindergarten to Eight Grade.* Washington, DC: National Academy Press. (http://www.nap.edu)

Duschl, R. (2000). Making the nature of science explicit. In R. Millar, J. Leech & J. Osborne (Eds.) *Improving Science Education: The contribution of research*. Philadelphia, PA USA: Open University Press.

Duschl, R. (1990). *Restructuring science education: The role of theories and their importance.* New York: Teachers College Press.

Duschl, R. & Grandy, R. (eds.) (2008). *Teaching Scientific Inquiry: Recommendations for research and implementation.* Rotterdam, Netherlands: Sense Publishers.

Eflin, J., Glennan, S. & Reisch, G. (1999). The nature of science: A perspective from the philosophy of science, *Journal of Research in Science Teaching* 36 (1), 107-116.

Feyerabend, D. (1975). *Against method*. London: Verso.

Ford, M. (2008). 'Grasp of practice' as a reasoning resource for inquiry and nature of science understanding. *Science & Education*, 17, 147-177.

Ford, M. J. & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. *Review of Research in Education, 30,* 1-32.

Giere R. (1988) *Explaining Science: a cognitive approach*. Chicago: University of Chicago Press.

Giere, R. (2002). Scientific cognition as distributed cognition. In P. Carruthers, S. Stich, & M. Siegal, Eds. (2002). *The cognitive basis of science.* (pp.285-299) Cambridge, UK: Cambridge University Press

Gitomer, D. H. (2008). Policy, practice and next steps for educational research. In Duschl, R. & Grandy, R. (Eds.) (2008) *Establishing a Consensus Agenda for K-12 Science Inquiry*, Netherlands: SensePublishers.

Gitomer, D. & Duschl, R. (2007). Establishing multi-level coherence in assessment. In P. Moss (Ed.). *Evidence and decision making, NSSE 2007 Yearbook*, V106, Issue 1.

Goldman, A. (1986). *Epistemology and Cognition.* Cambridge, MA: Harvard University Press.

Kesidou, S., & Roseman, J. E. (2002). How well do middle school science programs measure up? Findings from Project 2061's curriculum review. *Journal of Research in Science Teaching, 39*(6), 522–549.

Kitcher, P. (1993). *The Advancement of Science: Science Without Legend, Objectivity Without Illusions.* New York: Oxford University Press.

Klopfer, L. & Cooley, W. (1963). The history of science cases for high schools in the development of student understanding of science and scientists. *Journal of Research in Science Teaching*, *1*(1), 33-47.

Knorr-Cetina, K. (1999). *Epistemic cultures: How science makes knowledge.* Cambridge, MA: Harvard University Press.

Kuhn, T. (1970). *The Structure of Scientific Revolutions, 2nd edition.* Chicago: University of Chicago Press.

Lakatos, I. (1970) Falsification and the methodology of scientific research programmes. In I. Lakatos & A. Musgrave (Eds.) Criticism and the growth of knowledge. (pp. 91- 196) Cambridge: Cambridge University Press.

Lederman, N., Abd-el-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of Nature of Science Questionnaire: Towards Valid and Meaningful Assessment of Learners' Conceptions of the Nature of Science. *Journal of Research in Science Teaching, 39*(6), 497-521.

Lederman, N. & Abd-El-Khalick , F. (2002). *Views of Nature of Science Questionnaire: Toward Valid and Meaningful Assessment of Learners' Conception of Nature of Science;* Journal of Research in Science Teaching, 39, 497-521.

Lederman, N. & Lederman, J. (2004). "Revising instruction to teach nature of science: Modifying activities to enhance students' understanding of science". *The Science Teacher*, November.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching*, *29*(4), 331–359.

Lehrer, R. & Schauble, L. (2006). Cultivating model-based reasoning in science education. In K. Sawyer (Ed.), *The Cambridge handbook of the learning sciences.* New York: Cambridge University Press.

Lehrer, R., Schauble, L., & Lucas, D. (2008). Supporting development of the epistemology of inquiry. *Cognitive Development*, 23, 512-529.

Longino, H. (2002). *The Fate of Knowledge.* Princeton: Princeton University Press

Longino, H. (1990). *Science as Social Knowledge*. Princeton: Princeton University Press.

McComas, W. F., & Olson, J. K. (1998). The Nature of Science in International Science Education Standards Documents. In W. F. McComas (Ed.), *The Nature of Science in Science Education: Rationales and Strategies* (pp. 41-52). Dordrecht: Kluwer.

McComus, W., Ed., (1998). *The nature of science in science education: rationales and strategies.* Dordrecht: Kluwer.

National Research Council (2007). *Taking science to school: Learning and teaching science in grades K-8*. Washington, DC: National Academy Press.

Nersessian, N. (2002). The cognitive basis of model-based reasoning in science. In P. Carruthers, S. Stich, & M. Siegal, (Eds.) *The cognitive basis of science.* (pp. 133-153). Cambridge, UK: Cambridge University Press.

Nersessian, N. (2002). The cognitive basis of model-based reasoning in science. In P. Carruthers, S. Stich, & M. Siegal, (Eds.) *The cognitive basis of science.* (pp. 133-153). Cambridge, UK: Cambridge University Press.

Nersessian, N. (2008). Inquiry: How science works; Model-based reasoning in scientific practice. In R. Duschl & R. Grandy (Eds.) *Teaching Scientific Inquiry: Recommendations for research and implementation*. (pp. 57-79). Rotterdam, The Netherlands: Sense Publishers.

Niaz, M. (2009) *Critical appraisal of physical science as a human enterprise: Dynamics of scientific progress.* Milton Keynes, Springer.

Osborne, J. F., Ratcliffe, M., Collins, S., Millar, R., & Duschl, R. (2003). What 'ideas-about-science' should be taught in school science? A Delphi Study of the 'Expert' Community. *Journal of Research in Science Teaching, 40*(7), 692-720.

Pellegrino, J., Chudowsky, & Glaser, R. (2001). Knowing *What Students Know: The science and design of educational assessment.* Washington, DC: National Academy Press. (http://www.nap.edu).

Pine, J., Aschbacher, P., Roth, E., Jones, M., McPhee, C., Martin, C., Phelps, S., Kyle, T., Foley, B. (2006). Fifth graders' science inquiry abilities: A comparative study of students in hands-on and textbook curricula. *Journal of Research in Science Teaching, 43*(5), 467-484.

Quintana, C., Reiser, B. J., Davis, E. A., Krajcik, J., Fretz, E., Duncan, R. G., et al. (2004). A scaffolding design framework for software to support science inquiry. *Journal of the Learning Sciences, 13*(3), 337-386.

Rudolph, J. (2002). *Scientists in the Classroom: The cold war reconstruction of American science education.* New York: Palgrave Macmillian.

Sawyer, R.K., Ed., (2006). *The Cambridge Handbook of The Learning Sciences.* New York: Cambridge University Press.

Smith, C., Wiser, M., Anderson, C., & Krajcik, J. (2006). Implications of research on children'sLearning for assessment: Matter and atomic molecular theory. *Measurement: Interdisciplinary Research and Perspectives* (Vol. 4, pp. 11-98). Mahwah, NJ: Lawrence Erlbaum.

Smith, C., Maclin, D., Houghton, C., & Hennessey, M.G. (2000). Sixth-grade students' epistemologies of science: The impact of school science experience on epistemological development. *Cognition and Instruction, 18*(3), 285-316.

Taber, K. (2009) *Progressing Science Education: Constructing the Scientific Research Programme into the Contingent Nature of Learning Science*. Dordrecht: Springer

Thagard, P. (2007). Coherence, Truth, and the development of scientific knowledge. *Philosophy of Science, 74*(1), 28-47.

Thagard, P. (1992). *Conceptual revolutions*. Princeton, NJ: Princeton University Press.

Van Dijk, E.M. (2011). Portraying real science in science communication. *Science Education,*

Wilson, M. & Bertenthal, M. (Eds.) (2005). *Systems for State Science Assessment.* Washington DC: National Academies Press.

Zammito, J.H. (2004*). A nice derangement of epistemes: Post-positivism in the study of science From Quine to Latour*. Chicago: University of Chicago Press.

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."
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	"The Scientific	"Although no single	

(current position) 2000	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"	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*."	