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Nature of Science and Scientific Inquiry as Contexts for the Learning of Science and Achievement of Scientific Literacy

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Abstract

Although the reasons for concern about quality differ from nation to nation, the primary rallying point for science education reform is the perceived level of scientific literacy among a nation's populace. The essential nature of scientific literacy is that which influences students' decisions about personal and societal problems. Beyond this, however, educators work to influence students' ability to view science through a more holistic lens. Examining the philosophy, history, and sociology of science itself has the potential to engender perceptions of science, in the broader context, that can impact the lens through which students view the world. The integration of explicit, reflective instruction about nature of science (NOS) and scientific inquiry (SI) in traditional science content is addressed as a means through which the development of scientific literacy is fostered.

Key words: Nature of Science (NOS), Scientific Inquiry (SI), Scientific Literacy, Worldviews

Introduction

Over the years there have been numerous models of curriculum and instruction designed to improve the quality of science teaching and learning. In the end, all of these models are related to the construct of scientific literacy. The particular power of the Six Domains for Teaching and Assessing Science Learning model, used as the overarching framework for this paper, is its explicit reflection of the skills and abilities related to the construct of scientific literacy. Although the reasons for concern about quality differ from nation to nation, the primary rallying point for science education reform is the perceived level of scientific literacy among a nation's populace.

The present insistence on change, emphasized in reforms, for the sake of scientific literacy is not the first in science education's history. One can easily point to "critical" concerns voiced about science teaching and learning, and their associated reforms, for well over a century (Central Association of Science and Mathematics Teachers, 1907). In each case, whether the label "scientific literacy" was used or not, concerns have typically focused on the usefulness and relevancy of the subject matter included in K-12 science curriculum. The essential nature of scientific literacy is that which influences students' decisions about personal and societal problems. Beyond this, however, educators work to influence students' ability to view science through a more holistic lens. Examining the philosophy, history, and sociology of science itself has the potential to engender perceptions of science, in the broader context, that can impact the lens through which students view the world. The goal of science education remains scientific literacy, which ultimately impacts an individual's worldview.

Recent decades have seen the development and dissemination of science standards in Taiwan, China, Hong Kong, Australia, the U.S., South Africa, Germany and Chile, just to name a few. As with their predecessors these reform efforts have stressed the importance of conceptual understanding of the overarching ideas in science (e.g., cause and effect, equilibrium, structure and function, cycles, scale). Such ideas are believed to transcend the individual disciplines within science and are believed to be superior educational outcomes than the mere memorization of foundational discipline-based subject matter. The phrase "less is more" (American Association for the Advancement of Science [AAAS], 1993) has often been invoked to communicate the desire

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that instructional time focus on in-depth understanding of a reduced set of unifying scientific concepts. Although the words are different, the message remains quite familiar.

Worldviews and Scientific Epistemology

This article will focus on the dimension of the Six Domains for Teaching and Assessing Science model related to worldviews. It is this dimension that provides an overarching guiding framework for the teaching and learning of science and the achievement of scientific literacy. The concept of a worldview focuses on individuals' perceptions of their role in the world, the relationship of humans to the environment, and epistemology. In a sense, one's views of science are a sub-set of one's overall worldview. Consequently, specifically related to one's worldview is their view of scientific knowledge and how that knowledge is developed. The nature of scientific knowledge is often phrased as "nature of science" and one's perceptions of how scientific knowledge is developed are specifically related to scientific inquiry.

These epistemological constructs color the lenses through which individuals' view science, its implications and their lives in the context of science knowledge and practice. The values and beliefs that shape groups of individuals' frames of reference for making sense of the world constitute a worldview (Kawagley, Norris-Tull, & Norris-Tull, 1998) and while understandings about epistemology do not singularly determine a frame of reference, they have a decided influence (Allen & Crawley, 1998; Liu & Lederman, 2007; Matthews, 2008).
Helping students develop adequate conceptions of nature of science (NOS) and scientific inquiry (SI) has been an ongoing objective in science education (AAAS, 1990, 1993; Klopfer, 1969; National Research Council [NRC], 1996; National Science Teachers Association [NSTA], 1982). Indeed, most scientists and science educators have agreed upon this objective for the past 100 years (Central Association of Science and Mathematics Teachers, 1907; Kimball, 1967-68; Lederman, 1992; 2007). Presently, despite their varying pedagogical or curricular emphases, there is strong agreement among the major reform efforts in science education (AAAS, 1990, 1993; NRC, 1996) about the importance of enhancing students' conceptions of NOS and scientific inquiry. In fact, "the longevity of this educational objective has been surpassed only by the longevity of students' inability to articulate the meaning of the phrase 'nature of science,' and to delineate the associated characteristics of science" (Lederman & Niess, 1997, p. 1) or scientific inquiry. Despite numerous attempts, including the major curricular reform efforts of the 1960s, to improve students' views of the scientific endeavor, students have consistently been shown to possess inadequate understandings of several aspects of NOS and scientific inquiry (e.g., Aikenhead, 1973; Bady, 1979; Broadhurst, 1970; Lederman & O'Malley, 1990; Mackay, 1971; Mead & Metraux, 1957; Rubba & Andersen, 1978; Tamir & Zohar, 1991; Wilson, 1954).

Consequently, it is only natural to ask whether there are reasons to believe that the present reforms in science education are more likely to impact students' understandings than their predecessors. It is our view that the current reform documents' emphasis on NOS and scientific inquiry are likely to have as little impact as earlier efforts. Two critical and interrelated omissions that have typified previous efforts are, unfortunately, evident in the more recent reform documents. Furthermore, the Common Core standards presently being developed in the U.S. are even more remiss than this. There is not, and there has not been, a concerted professional development effort to clearly communicate, first, what is meant by "NOS" and scientific inquiry and second, how a functional understanding of these valued aspects of science can be communicated to K-12 students. Perhaps the lack of professional development related to NOS and scientific inquiry is a consequence of the misunderstanding that NOS and scientific inquiry fall within the realm of affect and process as opposed to cognitive outcomes of equal, if not greater, importance than "traditional" subject matter. Nature of science and scientific inquiry are just as much science content as the reactions of photosynthesis or pH. In reality, however, it is NOS and scientific inquiry that provide the context for the subject matter specified in the Standards and other reform documents. Furthermore, NOS permeates all areas of the discipline-specific standards and it is a critical component of the standards on "science as inquiry." From the perspective of currently advocated pedagogy (i.e., constructivist approaches), an understanding of NOS and scientific inquiry underlies the essence of the Teaching and Assessment Standards specified by the National Science Education Standards. It is not at all difficult to argue that a teacher who lacks adequate conceptions of NOS and scientific inquiry, and a functional understanding of how to teach these valued aspects of science cannot orchestrate the types of instructional activities and atmosphere, or assess students' progress, as specified in the various reform efforts in science education. Indeed, a functional understanding of NOS and scientific inquiry by teachers is clearly prerequisite to any hopes of achieving the vision of science teaching and learning specified in the various reform efforts. In the following sections, we will clarify the meaning of NOS and scientific inquiry. These terms are used with little precision and high variability within educational circles and it is necessary to insure that we are all consistent regarding these important educational outcomes. We will also delineate several misconceptions promoted (or ignored) by existing reform efforts. It will further be argued that without explicit instructional attention to NOS and scientific inquiry, students will once again learn science subject matter in a context-free environment. Such an environment does not permit the in-depth conceptual understanding of science subject matter advocated in the various visions of reform and will not help create a populace that can be considered scientifically literate.

What is NOS?

The phrase "nature of science" typically refers to the epistemology of science, science as a way of knowing, or the values and beliefs inherent to the development of scientific knowledge (Lederman, 1992, 2007). Beyond these general characterizations, no consensus presently exists among philosophers of science, historians of science, scientists, and science educators on a specific definition for NOS. This lack of consensus, however, should neither be disconcerting nor surprising given the multifaceted nature and complexity of the scientific endeavor. Conceptions of NOS have changed throughout the development of science and systematic thinking about science and are reflected in the ways the scientific and science education communities have defined the phrase "nature of science" during the past 100 years (e.g., AAAS, 1990, 1993; California Department of Education, 1990; Center of Unified Science Education at Ohio State University, 1974; Central Association for Science and Mathematics Teachers, 1907; Klopfer & Watson, 1957; NSTA, 1982).

It is our view, however, many of the disagreements about the definition or meaning of NOS that continue to exist among philosophers, historians, and science educators are irrelevant to K-12 instruction. The issue of the existence of an objective reality as compared to phenomenal realities is a case in point. We argue that there is an acceptable level of generality regarding NOS that is accessible to K-12 students and relevant to their daily lives. Moreover, at this level, little disagreement exists among philosophers, historians, and science educators. Among the characteristics of the scientific enterprise corresponding to this level of generality are that scientific knowledge is tentative (subject to change), empirically-based (based on and/or derived from observations of the natural world), subjective (theory-laden), necessarily involves human inference, imagination, and creativity (involves the invention of explanations), and is socially and culturally embedded. Two additional important aspects are the distinction between observations and inferences, and the functions of, and relationships between scientific theories and laws. Although many have opinions about the existence of subject matter specific conceptions of NOS and SI, the single empirical study in the area (Schwartz & Lederman, 2008) clearly shows that little disagreement exists across disciplines. Again, the critical point is to realize that the focus of this attention is on K-12 students. What follows is a brief consideration of these characteristics of science and scientific knowledge.

First, students should be aware of the crucial distinction between observation and inference. Observations are descriptive statements about natural phenomena that are "directly" accessible to the senses (or extensions of the senses) and about which several observers can reach consensus with relative ease. For example, objects released above ground level tend to fall and hit the ground. By contrast, inferences are statements about phenomena that are not "directly" accessible to the senses. For example, objects tend to fall to the ground because of "gravity." The notion of gravity is inferential in the sense that it can only be accessed and/or measured through its manifestations or effects. Examples of such effects include the perturbations in predicted planetary orbits due to inter-planetary "attractions," and the bending of light coming from the stars as its rays pass through the sun's "gravitational" field.

Second, closely related to the distinction between observations and inferences is the distinction between scientific laws and theories. Individuals often hold a simplistic, hierarchical view of the relationship between theories and laws whereby theories become laws depending on the availability of supporting evidence. It follows from this notion that scientific laws have a higher status than scientific theories. Both notions, however, are inappropriate because, among other things, theories and laws are different kinds of knowledge and one cannot develop or be transformed into the other. Laws are statements or descriptions of the relationships among observable phenomena. Boyle's law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point. Theories, by contrast, are inferred explanations about observable phenomena. The kinetic molecular theory, which explains Boyle's law, is one example. Moreover, theories are as legitimate a product of science as laws. Scientists do not usually formulate theories in the hope that one day they will acquire the status of "law." Scientific theories, in their own right, serve important roles, such as guiding investigations and generating new research problems in addition to explaining relatively huge sets of seemingly unrelated observations in more than one field of investigation. For example, the kinetic molecular theory serves to explain phenomena that relate to changes in the physical states of matter, others that relate to the rates of chemical reactions, and still other phenomena that relate to heat and its transfer, to mention just a few.

Third, even though scientific knowledge is, at least partially, based on and/or derived from observations of the natural world (i.e., empirical), it nevertheless involves human imagination and creativity. Science, contrary to common belief, is not a totally lifeless, rational, and orderly activity. Science involves the invention of explanations and this requires a great deal of creativity by scientists. The “leap” from atomic spectral lines to Bohr’s model of the atom with its elaborate orbits and energy levels is a case in point. This aspect of science, coupled with its inferential nature, entails that scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality.

Fourth, scientific knowledge is subjective or theory-laden. Scientists’ theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations actually influence their work. All these background factors form a mind-set that affects the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), and how they make sense of, or interpret their observations. It is this (sometimes collective) individuality or mind-set that accounts for the role of subjectivity in the production of scientific knowledge. It is noteworthy that, contrary to common belief, science never starts with neutral observations (Chalmers, 1982). Observations (and investigations) are always motivated and guided by, and acquire meaning in reference to questions or problems. These questions or problems, in turn, are derived from within certain theoretical perspectives.

Fifth, science as a human enterprise is practiced in the context of a larger culture and its practitioners (scientists) are the product of that culture. Science, it follows, affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded. These elements include, but are not limited to, social fabric, power structures, politics, socioeconomic factors, philosophy, and religion. An example may help to illustrate how social and cultural factors impact scientific knowledge. Telling the story of the evolution of humans (Homo sapiens) over the course of the past seven million years is central to the biosocial sciences. Scientists have formulated several elaborate and differing story lines about this evolution. Until recently, the dominant story was centered about “the man-hunter” and his crucial role in the evolution of humans to the form we now know (Lovejoy, 1981). This scenario was consistent with the white-male culture that dominated scientific circles up to the 1960s and early 70s. As the feminist movement grew stronger and women were able to claim recognition in the various scientific disciplines, the story about hominid evolution started to change. One story that is more consistent with a feminist approach is centered about “the female-gatherer” and her central role in the evolution of humans (Hrdy, 1986). It is noteworthy that both story lines are consistent with the available evidence.

Sixth, it follows from the previous discussions that scientific knowledge is never absolute or certain. This knowledge, including “facts,” theories, and laws, is tentative and subject to change. Scientific claims change as new evidence, made possible through advances in theory and technology, is brought to bear on existing theories or laws, or as old evidence is reinterpreted in the light of new theoretical advances or shifts in the directions of established research programs. It should be emphasized that tentativeness in science does not only arise from the fact that scientific knowledge is inferential, creative, and socially and culturally embedded. There are also compelling logical arguments that lend credence to the notion of tentativeness in science. Indeed, contrary to common belief, scientific hypotheses, theories, and laws can never be absolutely “proven.” This holds irrespective of the amount of empirical evidence gathered in the support of one of these ideas or the other (Popper, 1963, 1988). For example, to be “proven,” a certain scientific law should account for every single instance of the phenomenon it purports to describe at all times. It can logically be argued that one such future instance, of which we have no knowledge whatsoever, may behave in a manner contrary to what the law states. As such, the law can never acquire an absolutely “proven” status. This equally holds in the case of hypotheses and theories.

Finally, it is important to note that individuals often conflate NOS with science processes (which is more consistent with scientific inquiry). Although these aspects of science overlap and interact in important ways, it is nonetheless important to distinguish the two. Scientific processes are activities related to collecting and analyzing data, and drawing conclusions (AAAS, 1990, 1993; NRC, 1996). For example, observing and inferring are scientific processes. On the other hand, NOS refers to the epistemological underpinnings of the activities of science. As such, realizing that observations are necessarily theory-laden and are constrained by our perceptual apparatus belongs within the realm of NOS.

Professional development efforts designed for teachers must not conclude, as they have in the past, with the development of adequate teacher understandings. The research is quite clear that teachers’ understandings do not automatically translate into classroom practice. Certainly, teachers must have an in-depth understanding of what they are expected to teach. However, professional development efforts must also emphasize how teachers can successfully facilitate the development of students' understandings of NOS.

What is Scientific Inquiry?

Although closely related to science processes, scientific inquiry extends beyond the mere development of process skills such as observing, inferring, classifying, predicting, measuring, questioning, interpreting and analyzing data. Scientific inquiry includes the traditional science processes, but also refers to the combining of these processes with scientific knowledge, scientific reasoning and critical thinking to develop scientific knowledge. From the perspective of the National Science Education Standards (NRC, 1996), students are expected to be able to develop scientific questions and then design and conduct investigations that will yield the data necessary for arriving at conclusions for the stated questions. The Benchmarks for Science Literacy (AAAS, 1993) are a bit less ambitious as they do not advocate that all students be able to design and conduct investigations in total. Rather, it is expected that all students at least be able to understand the rationale of an investigation and be able to critically analyze the claims made from the data collected. Scientific inquiry, in short, refers to the systematic approaches used by scientists in an effort to answer their questions of interest. Pre-college students, and the general public for that matter, believe in a distorted view of scientific inquiry that has resulted from schooling, the media, and the format of most scientific reports. This distorted view is called THE SCIENTIFIC METHOD. That is, a fixed set and sequence of steps that all scientists follow when attempting to answer scientific questions. A more critical description would characterize THE METHOD as an algorithm that students are expected to memorize, recite, and follow as a recipe for success. The visions of reform, however, are quick to point out that there is no single fixed set or sequence of steps that all scientific investigations follow. The contemporary view of scientific inquiry advocated is that the questions guide the approach and the approaches vary widely within and across scientific disciplines and fields.

At a general level, scientific inquiry can be seen to take several forms (i.e., descriptive, correlational, and experimental). Descriptive research is the form of research that often characterizes the beginning of a line of research. This is the type of research that derives the variables and factors important to a particular situation of interest. Whether descriptive research gives rise to correlational approaches depends upon the field and topic. For example, much of the research in anatomy and taxonomy are descriptive in nature and do not progress to experimental or correlational types of research. The purpose of research in these areas is very often simply to describe. On the other hand, there are numerous examples in the history of anatomical research that have lead to more than description. The initial research concerning the cardiovascular system by William Harvey was descriptive in nature. However, once the anatomy of blood vessels had been described, questions arouse concerning the circulation of blood through the vessels. Such questions lead to research that correlated anatomical structures with blood flow and experiments based on models of the cardiovascular system. To briefly distinguish correlational from experimental research, the former explicates relationships among variables identified in descriptive research and the latter involves a planned intervention and manipulation of variables related in correlational research in an attempt to derive causal relationships. In some cases, lines of research can been seen to progress from descriptive to correlational to experimental, while in other cases (e.g., descriptive astronomy) such a progression is not necessarily relevant.

The perception that a single scientific method exists owes much to the status of classical experimental design. Experimental designs very often conform to what is presented as THE SCIENTIFIC METHOD and the examples of scientific investigations presented in science textbooks most often are experimental in nature. The problem, of course, is not that investigations consistent with "the scientific method" do not exist. The problem is that experimental research is not representative of scientific investigations as a whole. Consequently, a very narrow and distorted view of scientific inquiry is promoted in our K-12 students.

Scientific inquiry has always been ambiguous in its presentation within science education reforms. In particular, inquiry is perceived in three different ways. It can be viewed as a set of skills to be learned by students and combined in the performance of a scientific investigation. It can also be viewed as a cognitive outcome that students are to achieve. In particular, the current visions of reform are very clear (at least in written words) in distinguishing between the performance of inquiry (i.e., what students will be able to do) and what students know about inquiry (i.e., what students should know). For example, it is one thing to have students set up a control group for an experiment, while it is another to expect students to understand the logical necessity for a control within an experimental design. Unfortunately, the subtle difference in wording noted in the reforms (i.e., "know" versus "do") is often missed by everyone except the most careful reader. The third use of "inquiry" in reform documents relates strictly to pedagogy and further muddies the water. In particular, current wisdom advocates that students best learn science through an inquiry-oriented teaching approach. It is believed that students will best learn scientific concepts by doing science. In this sense, "scientific inquiry" is viewed as a teaching approach used to communicate scientific knowledge to students (or allow students to construct their own knowledge) as opposed to an educational outcome that students are expected to learn about and learn how to do. Indeed, it is the pedagogical sense of inquiry that it is unwittingly communicated to most teachers by science education reform documents, with the two former senses lost in the shuffle. Overall, what we want students to understand about the process of the development of scientific knowledge (i.e., scientific inquiry) is:

Communicating Functional Understandings of NOS

The tone of our discussion implies that science education reforms, currently and in the past, have mishandled NOS and scientific inquiry. On the one hand, it has been assumed that teachers understand both of these important aspects of science and little professional development has been planned or provided. On the other hand, little has been provided to teachers regarding the teaching of scientific inquiry and NOS to students. The provision of professional development is closely linked to financial resources and the purveyors of reform can hardly be held accountable for what school districts, counties, states, and countries decide to provide. One could argue, however, that reform documents could present a much stronger case for the necessity of professional development.

However, there is a critical flaw in the various reforms' approach to the teaching of the nature of science and scientific inquiry. It is this critical flaw that has existed since the beginning of the science education community's recognition of the importance of scientific inquiry and NOS as important educational outcomes. Two general approaches have been advocated by reform documents and the science education literature to enhance students' and teachers' understandings of NOS and/or scientific inquiry. The first approach, labeled here as an implicit approach, suggests that by "doing science" students will also come to understand NOS and scientific inquiry (Lawson, 1982; Rowe, 1974). This approach was adopted by most of the curricula of the 1960s and 70s that emphasized hands-on, inquiry-based activities and/or process-skills instruction. Research studies have indicated that the implicit approach was not effective in enhancing students' and teachers' understandings of NOS or scientific inquiry (e.g., Durkee, 1974; Haukoos & Penick, 1985; Riley, 1979; Spears & Zollman, 1977; Trent, 1965; Troxel, 1968). It should be noted that two interrelated assumptions underlie the implicit approach and compromise its effectiveness. The first depicts attaining an understanding of NOS and/or scientific inquiry to be "affective" (as compared to a cognitive) learning outcomes. Indeed, it is not uncommon to find scientific inquiry often referred to as "scientific attitude." This first assumption entails the second assumption; the assumption that learning about NOS and scientific inquiry will result as a by-product of "doing science."

The second approach, the historical approach (one that is strongly recommended by the National Science Education Standards and other reform documents), suggests that incorporating the history of science (HOS) in science teaching can serve to enhance students' views of NOS. History of Science Cases for High Schools (Klopfer & Watson, 1957) and Harvard Project Physics (Rutherford, Holton, & Watson, 1970) were two notable curriculum development efforts that included substantial attention to the HOS at the high school level. However, a review of the efforts that aimed to assess the influence of incorporating the HOS in science teaching (Klopfer & Cooley, 1963; Solomon, Duveen, Scot, & McCarthy, 1992; Welch & Walberg, 1972; Yager & Wick, 1966) indicates that evidence concerning the effectiveness of the historical approach is, at best, inconclusive. And, most recently, the work of Abd-El-Khalick (1998) has indicated that specific courses in the history and/or philosophy of science have little impact on students' understanding of NOS and scientific inquiry.

An alternative approach to the two often noted in the reforms suggests that the goal of improving students' views of the scientific endeavor "should be planned for instead of being anticipated as a side effect or secondary product" of varying approaches to science teaching (Akindehin, 1988, p. 73). This explicit approach uses instruction geared toward various aspects of NOS or scientific inquiry and utilizes elements from the history and philosophy of science to improve learners' views of NOS. In general, relative to the implicit and historical approaches, the explicit approach has been more effective in helping learners achieve enhanced understandings of NOS and scientific inquiry (e.g., Akindehin, 1988; Billeh & Hasan, 1975; Carey & Stauss, 1968, 1970; Jones, 1969; Lavach, 1969; Ogunniyi, 1983; Olstad, 1969).

It is our opinion that a functional understanding of NOS and/or scientific inquiry is best facilitated through an explicit reflective approach. We cannot overemphasize the importance of taking time, at the conclusion of any activity, to explicitly point out to students the aspects of NOS and scientific inquiry that are highlighted. To encourage reflection, teachers must discuss with students the implications such aspects of NOS and scientific inquiry have for the way they view scientists, scientific knowledge, and the practice of science.

In conclusion, it is important to emphasize that we should no longer assume that students will come to understand NOS or scientific inquiry as a by-product of "doing" science-based or inquiry activities. Nor should we assume that if teachers understand NOS and scientific inquiry, they will automatically teach in a manner "consistent" with those understandings. NOS and scientific inquiry should be thought of as a "cognitive" rather than as an "affective" instructional outcomes. If K-12 students are expected to develop more adequate conceptions of NOS and scientific inquiry, then, as any cognitive objective, this outcome should be planned for, explicitly taught, and assessed. All this can be facilitated through concerted and continued professional development efforts designed to promote science teachers' understanding of NOS and scientific inquiry, provide approaches teachers can use to facilitate students' conceptions, and foster commitment to the idea that NOS and scientific inquiry are instructional objectives of primary importance that permeate all aspects of curriculum and instruction.

Concluding Remarks

This discussion began by distinguishing current reform efforts in science education from their predecessors with respect to the heightened interest and emphasis on scientific inquiry and NOS. The primary reason for this heightened, but certainly not new, advocacy is the belief that students need to develop in-depth understandings of how scientific knowledge is generated and the implications this has for the status of the knowledge. Science educators have come to believe that if students understand the source and limits of scientific knowledge they will be better equipped to make informed decisions about personal and societal problems that are scientifically-based. In short, understandings of NOS and scientific inquiry are believed to be critical and essential components of the modern day battle cry of "scientific literacy."

With respect to students' achieving in-depth understanding of subject matter, which is another component of the current reform efforts, it can be argued that such a goal is unachievable unless students understand NOS and scientific inquiry. For example, can it be said that a student truly understands the concept of a gene if he/she does not realize that a "gene" is a construct invented to explain experimental results? Does the student who views genes as possessing physical existence analogous to pearls on a necklace possess an in-depth understanding of the concept? Does the student who is unaware that the atom (as pictured in books) is a scientific model used to explain the behavior of matter and that it has not been directly observed have an in-depth understanding of the atom?

Misconceptions about the scientific validity of biological evolution commonly appear in the media and courts of law. Many of these misconceptions relate to whether evolution is a testable scientific theory. The arguments against the validity of evolution usually proceed to point out that evolution cannot be tested using the scientific method. Therefore, evolution cannot be a valid scientific theory. Many feel that the problem is at least partially created by the public's misunderstanding of scientific inquiry and/or scientific theory. These few examples should make it clear that understanding NOS and scientific inquiry provide a guiding framework and context for scientific knowledge. Without an understanding of how scientific knowledge is derived and the implications the process of derivation has for the status and limitations of the knowledge, all students can ever hope to achieve is knowledge without context. Context is necessary for students to understand what the knowledge means. In short, lack of context is the equivalent to playing a game of chess without knowing the rules of the game. Unless students can derive meaning for the scientific knowledge they acquire, there is little hope that they can use their knowledge to make informed decisions.

In many ways the state of science education and science education reform is exactly where it was 100 years ago. We continue to seek the holy grail of in-depth understanding of scientific concepts for our K-12 students, just as we did at the turn of the 20th century. We have progressed in the realization that students cannot meaningfully learn a long laundry list of terms, vocabulary, and factoids. We have recognized the sensibility of attempting to focus our educational efforts on fewer, unifying themes/concepts. However, we continue to fail at providing students with the most important organizing themes of all, NOS and scientific inquiry. Despite volumes of research we continue to believe that students will come to understand scientific inquiry and NOS simply by "doing science." Such an expectation is equivalent to assuming that individuals will come to understand the mechanism of breathing simply by breathing. Obviously, this is not the case. Doing science is certainly a start, but students need to reflect on what it is they are doing. They need to be engaged in discussions of why scientific investigations are designed in certain ways. Students need to discuss the assumptions inherent to any scientific investigation and the implications these assumptions have for the results. Furthermore, students need to discuss the fact that science is done by humans and this has implications for the knowledge that is produced. These questions are but a few and you can certainly develop many more. Our point, however, is quite simple. NOS and scientific inquiry need to be addressed explicitly during science instruction. They need to be given status equal to that of traditional subject matter. Would we ever expect a student to implicitly learn pH? Without such explicit instructional attention, students will continue to learn subject matter without context and the visions of reform in science education will progress no further than they have in the past.

Back to the Future

Science classrooms have an obligation to communicate the concepts and processes of science disciplines. However, the reality of too many classrooms is that students' experiences with and perceptions of the content and practice of science are limited almost exclusively to these domains. The emphasis of reforms on the development of scientific literacy necessitates that students' are armed with the habits of mind (AAAS, 1990, 1993) to make informed decisions about personal and societal problems. Understandings about nature of science and scientific inquiry are a context for those habits to develop. They are also both subject to, and a subset of, an individual's worldview.

The context illuminated by understandings about NOS and SI is that of science, scientific practice and its implications. The development of those understandings, however, takes place within an individual's frame of reference. The value judgments, beliefs, perceptions and experiences that they bring to that process play an important role and, ultimately, science curriculum needs to consider students' worldviews (Liu & Lederman, 2007). This domain, from the six domains model, as emphasized in this paper illustrates the culmination of five areas of emphasis: concepts, processes, creativity, attitudes and applications and connections in a worldview context that examines the history, philosophy and sociology of science as a whole. The development of the scientifically literate students and populations sought by the many present reform efforts necessitate curricular and pedagogical attention to this domain and therefore to the subset of epistemological understandings, NOS and SI. Existing research illustrates the critical importance of explicit, reflective instruction in the development of understandings about these constructs (Lederman, 2007). Until reforms and classrooms consistently reflect what we know to be needed, our ability as educators to influence the development of informed conceptions of nature of science and scientific inquiry and therefore scientific literacy will remain hampered.

We recommend that attention to NOS and SI be integrated into instruction focusing on "traditional" subject matter. This is the most feasible way to address the importance of NOS and SI without sacrificing, but problem energizing, students' learning of foundational science concepts. For example, when students are studying genomics and the personal and societal decisions this area of study brings, it is critical for the teacher to engage students in a discussion of how our knowledge has developed and its inherent ontological status. Without such knowledge, students' will be compromised in their ability to make informed decisions. Without such knowledge, students will not be able to emulate the desired goal of scientific literacy. Naturally, this will require more complex planning and enactment of instruction. However, the alternative is far less than we deserve as a global community.

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