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Ideas for enhancing primary and high school science education

Did you Know?

Atmospheric Carbon Dioxide

During 2005, carbon dioxide levels in the atmosphere rose to 381 parts per million (ppm), which is 100 ppm above the average in the pre-industrial age. What is more, the levels are rising at twice the rate of 30 years ago. Humans certainly appear to be changing the earth's climate.

Connecting Inquiry and the Nature of Science

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Abstract

Inquiry has been one of the most prominent reforms in science education. One of the goals of teaching through inquiry methods is to enable students to have experiences that are authentic to scientists' experiences. Too often, inquiry science is taught as either the "scientific method" or as "hands-on," disconnected activities (Bybee, 2004), which is only a sliver of the continuum of experiences inquiry science offers. Quality inquiry investigations can be implemented by using the aspects of the nature of science, the inherent understanding that scientists use to generate knowledge, as a guide. Often, process skills and the nature of science are confused due to their close relationship. Process skills are necessary for inquiry science, but do not provide the underlying concepts that guide the development of scientific knowledge. The aspects of the nature of science provide the rationale for the importance of process skills and how these skills are used to develop new scientific knowledge. The research literature converges on seven aspects of the nature of science that defines science as a discipline: 1. Scientific knowledge is durable, yet tentative; 2. empirical evidence is used to support ideas in science; 3. social and historical factors play a role in the construction of scientific knowledge; 4. laws and theories play a central role in developing scientific knowledge, yet they have different functions; 5. accurate record keeping, peer review, and replication of experiments help to validate scientific ideas; 6. science is a creative endeavor; and 7. science and technology are not the same, but they impact each other (Lederman & Lederman, 2005; McComas, 2005). Each aspect of the nature of science is discussed in detail, with examples demonstrating how to explicitly incorporate the nature of science into classroom inquiry investigations. Teachers can help students learn to independently monitor their own learning and think scientifically by using the nature of science as a guide for inquiry investigations.

One of the most prominent reforms in science education is inquiry science (American Association for the Advancement of Science [AAAS], 1993). The *National Science Education Standards* (National Research Council, 1996) refer to scientific inquiry as “the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work” (p. 23). When science content is taught through inquiry methods, student understandings and explanations about the real world improve and learning is more meaningful (Hogan, 2000; Hogan & Maglienti, 2001;). One of the goals of teaching through inquiry methods is to enable students to have experiences that are aligned more closely to scientists’ experiences. Too often, inquiry science is taught as either the “scientific method” or as “hands-on,” disconnected activities (Bybee, 2004), which is only a sliver of the continuum of experiences inquiry science offers. How can teachers guide students to more significant scientific experiences? When students are constructing their knowledge from open-ended inquiry investigations, what can teachers do to promote scientific thinking?

Process Skills and the Nature of Science

Because methods of inquiry science attempt to make students’ experiences authentic, they should be guided by the inherent guidelines of the discipline of science. If students don’t understand the principles by which scientists conduct research, then their inquiry experience would not be meaningful in a scientific way. Students could go through the motions of doing an experiment and become proficient in the process skills that are required for scientific investigation, but they may not be thinking like scientists. Process skills are necessary for inquiry science, but are often mistaken for the underlying concepts that guide the development of scientific knowledge. The aspects of the nature of science provide the rationale for the importance of process skills and how these skills are used to develop new scientific knowledge. Table 1 shows connections between process skills and the nature of science. The nature of science, the inherent guidelines that are used to conduct methods of discovering scientific knowledge, provides the underlying principles that show students why the correct choice and use of process skills will lead to scientific knowledge.

Using the Nature of Science to Provide Quality Inquiry

Open-ended inquiry can be daunting because of the countless numbers of outcomes of student-initiated investigations. A classroom teacher could not be expected to know in advance all of the outcomes of possible student investigations, so how can the quality of the investigation be guaranteed? Students can have quality inquiry experiences when they reflect on the nature of science in their decisions regarding research questions, procedures, measurement techniques, data recording methods, and reporting methods. The teacher can be a resource by offering ideas to the student so that the investigation in conducted in a scientific way. The teacher can be a filter, making sure all student decisions correspond to the nature of science. For example, in an investigation exploring the effect of the type of material used to restrict heat transfer from boiling water, students may decide to measure only three trials for each type of material. The teacher should intervene and ask students if data would be reliable if the three trials produced drastically different results. The teacher could lead students to understand that a greater number of trials make the results more valid. Table 2 lists some possible teachable moments regarding investigations and the nature of science. Even if an investigation proves to be inconclusive, the students gained the experience of how knowledge is obtained in a scientific realm.

Table 1
Connections Among Inquiry Activities, Process Skills, and the Nature of Science

Inquiry activity	Process skill	Nature of science concept
Using senses to identify phenomena	Observation	Empirical evidence is used to support ideas.
Organizing information so that it is accessible	Classification	Knowledge production in science shares common factors; science is a creative endeavor.
Using tools to quantify phenomena	Measurement	Science and technology impact each other, but are not the same.
Creating data tables	Organization of data	Accurate record keeping, peer review, and replication of experiments help to validate scientific ideas.
Working in groups	Cooperation, collaboration	Social and historical factors play a role in the construction of scientific knowledge.
Connecting ideas to other activities	Generalizing	Theories help to connect and explain scientific facts. Scientific knowledge is durable, yet tentative.

Elaborating the Nature of Science

During the past 10 years, the thinking of researchers on aspects of the nature of science has converged, and more recently there has been agreement on some of the elements of the nature of science (Lederman, 1992; McComas, Almazroa, & Clough, 1998). The research literature converges on seven aspects of the nature of science that defines science as a discipline: 1. Scientific knowledge is durable, yet tentative; 2. empirical evidence is used to support ideas in science; 3. social and historical factors play a role in the construction of scientific knowledge; 4. laws and theories play a central role in developing scientific knowledge, yet they have different functions; 6. accurate record keeping, peer review, and replication of experiments help to validate scientific ideas; 6. science is a creative endeavor; and 7. science and technology are not the same, but they impact each other (Lederman, Abd-El-Khalick, Bell, & Schwartz, 2002; McComas, 2005). When guided by the nature of science, student inquiry can become more than merely following the “scientific method.” Even when students pose unique research questions and the outcomes of the investigation are unknown, teachers can feel confident that students will receive meaningful scientific experiences when the nature of science is used as a guideline for the inquiry. A deep understanding of each aspect of the nature of science will help facilitate quality inquiry investigations.

The idea that scientific knowledge is durable, yet tentative, is difficult for many students to understand. After all, the content that makes up scientific knowledge is printed in the book, and resembles the “answers” to how the world works. Many students have had the experience of memorizing facts their entire school career, so students may experience difficulties when faced with the thought that these facts can change, based on new data. At the beginning of the year, I confront the idea that science content is in its final form by introducing students to “sewer slugs” (McCormack, 1990). I explain in the form of a demonstration that three slugs can biologically convert 50 mL of urine to potable water in 1 minute and 30 seconds. I then produce a beaker of “urine” and place the slugs in the urine. The slugs begin swimming around in the urine. I ask students to make observations and I record the observations on the board, carefully pointing out which statements are observations and which are inferences. After all observations have been made, I drink the urine and snack on a few of the slugs. When students have gotten over their disgust in the demonstration, they begin to wonder how it worked. They experience cognitive dissonance because what they just saw doesn’t fit with what they think. Based on the new information that I would drink the urine and eat the slugs, students reconfigure their thinking and ask probing questions. They eventually find out that the urine was soda with food coloring and the slugs were raisins. A discussion about why the raisins “swim” connects their observations of the bubbles sticking to the raisins to the topic of buoyancy. During this activity, I take time to explicitly talk about the changes in their thinking when confronted with new information. Scientists, when confronted with new information, must also think about how the new information fits in with the old information. In this way, scientific knowledge is tentative, yet durable.

Table 2
Using the Nature of Science to Promote Quality Inquiry

Aspect of the nature of science	Opportunities to show scientific thinking during inquiry
Scientific knowledge is durable, yet tentative.	Take a discrepant event, such as “sewer slugs,” and have students make observations given only limited information. Disclose more information about the situation and discuss how students’ ideas have changed given the additional information.
Empirical evidence is used to support ideas in science.	Where possible, base observations on a standard of comparison, such as a measurement system, and ensure all observations are free of judgment and recorded accurately.
Social and historical factors play a role in the construction of scientific knowledge.	Demonstrate how scientific achievements sometimes occur in short spurts over a length of time, and that each idea is built on prior knowledge, such as the development of the structure of DNA.
Laws and theories play a central role in developing scientific knowledge, yet they have different functions.	Ask students how their prior knowledge affected the results. Did their results correspond with their expectations, or did they experience cognitive dissonance? How did their observations help to build ideas about their topic? Did students follow the rules of a phenomenon (using laws) or did they try to explain the mechanisms involved (using theory)?
Accurate record keeping, peer review, and replication of experiments help to validate scientific ideas.	Have students trade data tables with another group and have the group explain what the data table means. After inquiry investigations are complete, have students present the results to their peers for evaluation.
Science is a creative endeavor.	How is the investigation different from experiments that have already been performed? What new ideas did you have to create to connect your observations to your conclusions?
Science and technology are not the same, but they impact each other.	How are scientific ideas different from technology? Identify the ideas used in the inquiry and the technology used in the inquiry. How did they impact each other?

Most students understand that science is different from other ways of knowing because ideas are supported by empirical evidence. Teachers can use inquiry investigations, with explicit reference to the nature of science, to enhance student understanding of evidence that is free from bias. Objective evidence can be compared against a standard. For example, the conclusion that "the change in temperature was big" is not based on objective evidence, because not everyone can agree on the meaning of the term *big*. An objective statement would be "the change in temperature was 15°C," which is a statement that includes a standard measurement. Whenever possible, students should strive to collect data that is objective. Teachers can encourage students to write more objective observations by asking them if other students could understand what is meant by their recorded observations. Trading data sets emulates the way the scientific community shares information through publications and replication of experiments.

The idea that social and historical factors play a role in the construction of scientific knowledge is a difficult one to present, especially if only content is presented in classrooms. History and sociology are difficult to fit into class lessons because they encompass large periods of time, whereas much of the historical focus in science is on singular experiments. One way to show students that some scientific achievements occur in short spurts of progress over long periods of time is to teach the history of the development of the ideas involving the structure and makeup of DNA. Gregor Mendel, although not directly addressing the structure of DNA, was important in developing the ideas of genes and heredity in the 19th century. The next breakthrough in understanding DNA did not occur until 1928, when Frederick Griffith was trying to find a vaccine against streptococcus pneumoniae. In his experiments, he injected two different strands of bacteria into mice, one that was harmless and one that was harmful. In his first experiment, he injected harmless live bacteria into the mice and they lived. In his second experiment, he injected the live harmful bacteria into the mice and they died. In his third experiment, he killed the harmful bacteria with heat and injected them into the mice and the mice lived. In his fourth experiment, he added live harmless bacteria to the dead harmful bacteria and the mice died. Since Griffith did not destroy the hereditary material, the disease continued to propagate. Picking up on Griffith's work, in 1944 Oswald Avery found that it was not protein, but DNA that carried hereditary substances. Erwin Chargaff figured out the equations for the different DNA bases in 1952 and Rosalind Franklin followed closely behind in 1953 with her photo of the DNA molecule. In April of 1953, James Watson and Francis Crick came up with the double helix structure. This progression points out two important aspects of the history of science; namely, that ideas usually build upon each other over time, and that scientific ideas sometimes occur in short segments over long periods of time.

Younger students find it difficult to relate to abstract sociological factors, making this topic even more difficult to teach. Another way to emphasize the impact of social factors on science is to have students recognize how their lab groups interact socially to develop knowledge. After groups of students conduct identical inquiry investigations, have students compare their results. Usually, the results among the groups will be slightly different. A whole-class discussion can look into how the differences occurred and the implications that student interactions had on the results. For example, if one student dominated the lab equipment and made all of the measurements, that student greatly influenced the data. If all students in a group took measurements, then erroneous measurement techniques might have been identified because more than one person contributed to the measurement techniques. The discussion could be broadened to focus on the whole scientific community and the cultural and sociological influences that impact science today.

Most students can define laws and theories according to their textbook, but students often lack the ability to explain the role of laws and theories in developing scientific knowledge. Students often misunderstand a law to be a higher form, or a more agreed-upon form, of a theory (McComas, 1998). Dunbar (1995) makes a useful distinction between laws and theory by calling laws the rules to be followed, whereas theoretical science attempts to explain why the rules work. When students understand that they use laws to apply rules in order to predict outcomes and theories are applied to explain phenomena, they may better grasp that theories and laws are two different types of knowledge. Understanding that laws and theories are different types of knowledge puts students in a better position to articulate their own scientific thinking.

Students may be better able to understand the central role of laws and theories by reflecting on the theories that they currently have. Using the word *theories* may turn some students off immediately, so a more appropriate approach may be to ask what students already know about the inquiry topic being studied. By tapping into their prior knowledge, teachers can begin to grasp the current theories the students use to operate. Observations made by students in inquiry investigations are greatly influenced by students' current cognitive theories. For example, student A has experience observing how water will run from a high point to a low point and carry small amounts of soil to another location. Student B has no experience with erosion or deposition. When both students are given a picture of a landscape and asked to identify where erosion might occur, student A uses his or her prior experiences to find a slope where water might carry soil from a high position to a low position. Student B has no prior ideas upon which to base an answer, and might choose a location based on where he or she thinks water is more likely to fall. Student B's lack of theories inhibits the ability to assimilate new knowledge. Conversely, new observations help to build theories. In the same situation, Student B may be sufficiently intrigued by the erosion question to do some independent investigation. A model terrain with hills and valleys is built and water poured from a watering can to simulate rain. Observations about how the water runs and the water's ability to carry soil from one place to another are used to make generalizations about the characteristics of erosion. Additional observations in different contexts help to codify his or her personal theory about erosion. Meaningful learning occurs when students' personal theories more closely resemble theories accepted by the scientific community.

Accurate record keeping, peer review, and replication of experiments can be integrated into inquiry investigations through initial requirements. Teachers can arrange classroom environments so that the importance of the legitimacy of student data sets and conclusions is central to the task of inquiry. Often students ask: "Should I write down what I saw, or record what should have happened?" Students have preconceived ideas regarding the outcome of their inquiry and try to fit their observations to their prior ideas, even if they conflict. Scientists spend a great deal of time ensuring their data and conclusions are beyond reproach, because their credibility depends on it. Teachers can encourage accurate record keeping, peer review, and replication of experiments by asking students to evaluate each other's inquiry investigation reports. Requiring peers to ask clarification questions is an effective way to transfer the content, as well as the process, from one group of students to another. Students can teach each other the information they learned through their inquiry experiment, as well as teach how the information was obtained.

Students often view science as an activity lacking creativity, where observations are reported and this evidence supports or refutes a hypothesis. From this understanding, a conclusion can be reached. To generalize observations that can lead to a new understanding of a particular topic takes creativity. Creativity can be demonstrated in the science class by encouraging students to investigate relationships that are unknown to them, because student learning may be optimized in such circumstances. When students are unaware of the outcome of an inquiry, they can't impose their preconceived ideas about a topic on the data or conclusions. Posing a challenge to build a car that runs exactly 10 meters, using only the energy of two 1-kilogram weights dropping a distance of 1 meter, offers students a creative environment that requires the application of science content. Students must think about the mechanisms that will transfer energy from the dropping weights to the propulsion of the car. Once students begin to understand about the amount of force needed to propel their cars, they must also wrestle with ways to solve the problem of halting the car at the ten meter mark. On a broader scale, geologists are required to think in a creative way when performing retrodiction. They must construct rigorous explanations to make up for gaps in the information provided. For example, geologists must find creative ways to explain how tectonic plates fit together in the light of fossil records and plate boundaries.

Lastly, students can deepen their epistemological understanding about scientific knowledge when they can see the differences between science and technology. Often students confuse science and technology because of the impact they have on each other. Generally, scientific ideas help to further technology. When technology advances, mainly in the form of measurement instruments, more data is contributed to scientific thinking, which in turn advances scientific theories. For example, ideas regarding the movement of planets were very different before the invention of the telescope. Because observations could only be made with the unaided eye, the prevailing idea in science was that all other planets and the sun revolved around the Earth. After the invention of the telescope, a technological achievement, the movement of other planets could be documented and the idea that all planets revolved around the sun became the prominent scientific idea. In this example, sociological factors slowed down the acceptance of the heliocentric model! In order to identify the concepts in science and the concepts regarding technology, students can be asked to reflect on their selection of measurement techniques. If they chose a different method, or a different precision of measurement, how might that influence their conclusions? How might more sophisticated tools change their ideas in the inquiry investigation? How might the measurement of pH using pH paper, universal indicator, or a pH meter be different?

The teacher’s role in open-ended inquiry is vital to the quality of content achieved in the outcome and to the quality of scientific thinking used throughout the investigation. When teachers effectively monitor students’ decisions and their alignment to the discipline of science, two learning goals are achieved: Students understand the scientific content investigated because they understand how it was obtained, and they understand what they learned in light of current theory. Teachers can use the nature of science as a guide for open-ended inquiry investigations to enable students to think scientifically. Many of the barriers teachers find in conducting inquiry investigations can be overcome with a deep understanding of the nature of science. Teachers can help students become lifelong learners, and help students think like scientists, by using the nature of science as a guide for inquiry investigations.

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Reassessing Possible Naturalized Ideology Regarding Science, Education, and Religion

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Abstract

This manuscript asks questions about what may be the naturalized, or taken for granted, ideologies in science education regarding religion. There have been times in history when religion has taken a dogmatic role in limiting the practices of science (e.g., the Roman Catholic Church and Galileo). This manuscript reflects on the dogmatic rule of religion and argues that now science may be in danger of imposing dogmatic ideals through reaching beyond the capacities of an empirical way of knowing. A Science, Technology, and Society (STS) approach to science teaching is considered as a possible mechanism for honoring both science and religion as valid yet different ways of knowing and better addressing students' integration of science learned in school into their everyday lives.

> Absence of evidence is not evidence of absence. (Roy, 2006)
>
> Behe's conclusion is that since complex biochemical systems in advanced organisms could not have evolved through strict Darwinian evolution, the only possible explanation is that the system was designed and put into place deliberately. (Card, 2006, ¶ 10)

These two quotes, in differing ways, get at relevant imperatives that I believe should be considered in science education. In his address, Rustum Roy (2006), Evan Pugh Professor of the Solid State, Professor of Geochemistry, and Professor of Science, Technology, and Society at The Pennsylvania State University, discussed the "change in guard" that he believes has taken place since the days of the Roman Catholic Church in the time of Galileo. In this earlier period, the Roman Catholic Church belief system, or worldview, represented what could be described as the dogma of the time, "a definite authoritative tenet" (Merriam-Webster Online dictionary). The change in guard that Roy argues has taken place, which may be accurate, is the new rule of Science. Roy posited that science has taken the role of the dogmatic authority of today.

Feyerabend (1975) illuminated dangers associated with an unchecked dogmatic rule of science in his writings pertaining to the potential dangers of an objective search for truth that disconnects the humanity from science and in his critique of rigid methodologies portrayed as the norms of scientific investigations. Feyerabend (1978) also argued that science should be separated from the