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The Science Teacher
November 2004, p. 28-31
Feature

The Nature of Science: Always Part of the Science Story

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Accurately conveying the nature of science (NOS)—what science is and how it works—is common to most science education standards documents (McComas and Olson 1998), including the *National Science Education Standards* (NRC 1996) and *Science for All Americans* (AAAS 1989). Understanding how science works is crucial to scientific literacy because bound up in content and public policy decisions involving science are issues regarding what science is, how knowledge in science comes to be accepted, and what science can and cannot do. Mistaken ideas of science likely affect students' attitudes toward science and learning in science classes.

Science courses in the United States have been described as a mile wide and an inch deep (Schmidt et al. 1999), so NOS may be viewed simply as another topic to add to an already overstuffed curriculum. However, all science teachers and courses teach students about NOS whether or not they wish to. A few of the ways mistaken notions about NOS are conveyed to students include

- the language science teachers use when teaching science content,
- the cookbook nature of many laboratory activities that convey mistaken notions about the processes of science,
- textbooks that report the end products of science without addressing how the knowledge was developed, and
- common assessment strategies that emphasize vocabulary and the final form conclusions of science.

Since implicit and explicit messages regarding NOS are present in all science courses, the issue is not whether a science course should address NOS, only what image will be conveyed to students. Fortunately, many strategies are available for science teachers to convey an accurate story about NOS.

Specific strategies

Introducing NOS
An engaging card-exchange activity that introduces students to NOS while providing the teacher with key insights into student thinking has been provided by Cobern and Loving (1998). In this activity, cards describing different views regarding scientists and how science works (e.g., "science knowledge is of much greater value than any other type of knowledge," or "good science always begins with observations") are distributed to students who must sort and trade cards in an effort to acquire a set that best represents their own NOS views. The activity not only engages students to consider their views on these topics, but also gives teachers a window into their students' thinking. Aware of students' views, teachers can use activities that challenge students' NOS misconceptions.

Puzzle-solving activities (Clough 1997)—in which teachers have students solve brainteasers and then consider how solving such puzzles is like doing science—can challenge students' thinking and provide more accurate understandings about how science works. Other activities include multiple variations of the common "black-box" activity in which students explore a system (such as a sealed box containing common objects or a sealed tube with protruding ropes; see Lederman and Abd-El Khalick 1998) and attempt to account for how it works, never being able to directly see its interior.

Pictorial gestalt switches are an engaging way to help students understand that observations depend on prior knowledge and are not objective (Michaels and Bell 2003). Examples include popular old/young lady and rabbit/duck images, geometrical images that fool the mind, and many of M.C. Escher's drawings (home.comcast.net/~davemc0/Escher). These can be used to illustrate how different interpretations can be constructed from the same data. Activities that require students to take a limited data set and make inferences, such as the "Look Before You Leap" activity described in this issue's Idea Bank section, are excellent ways to begin accurately portraying NOS to students.

The importance of language
Throughout the school year, accurately portraying NOS while teaching science content may be accomplished in a number of ways (Clough 1997, 2004). Teaching science content in a manner faithful to NOS necessitates that teachers carefully use language when teaching science. Words such as *law*, *theory*, *prove*, and *true* should be used carefully and students should be made aware of the importance of these words' meanings. Statements such as "What did the data tell us?" or "What do the data show?" misportray NOS because data do not tell scientists what to think. When providing evidence for

science ideas, NOS can seamlessly be incorporated by pointing out to students that the data are not telling the scientists what to think. Instead, scientists typically ask, "What *ideas can be developed* to *account for* the data?" This subtle but important shift in language creates opportunities to pose fruitful questions such as, "How does the need to make sense of data account for disagreements among scientists and the inventive character of science?"

Laboratory activities

Even though teachers see laboratories as a way to make science come alive, far too many laboratory activities distort NOS and reinforce students' misconceptions. Cookbook laboratory experiences imply that scientists are absolutely objective, that they follow prescribed steps in doing research, and that their conclusions follow obviously from the data collected. Typical laboratory instructions imply a step-by-step method for doing science and that doing science does not require creativity. Such experiences wrongly teach students that following procedures carefully will result in certain knowledge. Instead, use well-designed inquiry laboratory activities, and overtly draw students' attention to important NOS issues as they analyze laboratory procedures, interpret data, create procedures, and raise questions to be investigated. During such experiences, explicitly raise questions and ideas that help students understand the creative side of science, that data does not speak for itself and must be interpreted in light of other knowledge, the impossibility of absolute objectivity, the implausibility of a universal step-by-step method, and other important ideas about how science works.

Science textbooks and NOS

Science textbooks are notorious for downplaying human influences in research, sanitizing the processes that eventually result in knowledge, and portraying science as simply a lengthy list of conclusions. In the few instances when textbooks do mention scientists, the process of science is sanitized through statements such as, "In 1953 Watson, Crick, and Wilkins discovered the structure of DNA and in 1962 were awarded the Nobel Prize." Such phrases severely distort NOS by

- neglecting the crucial role of Rosalind Franklin and others in this achievement,
- ignoring alternative ideas given considerable attention (triple helices and like-with-like nitrogen base pair bonding) but later abandoned, and
- implying by the word *discovered* that the structure was found rather than created to account for data that were often very difficult to interpret.

A valuable strategy to implement periodically throughout the school year is to have students critically analyze their textbook's portrayal of NOS. Students can consider how written materials distort or ignore the

- meaning of words such as *law, hypothesis, theory* , and *prove* ;
- human side of science;
- assumptions underlying knowledge;
- difficulties in research including making sense of data; and
- justification for conclusions.

Assessment

Teachers should ensure that formal tests, laboratory write-ups, and other assignments emphasize NOS. For example, on a chemistry examination students can be referred back to a laboratory activity regarding the kind of substances or products formed when $NaHCO_3$ (*aq*) and $CaCl_2$ (*aq*) react (Clough and Clark 1994) and asked how the activity accurately and inaccurately portrays NOS. On a biology exam students might address experimental work done in the mid-twentieth century regarding the identification of DNA as the genetic material, the resistance by some scientists to accept that interpretation, and what that episode illustrates about NOS. The important message here is that an accurate story about NOS can be consistently communicated in a way that also bolsters students' understanding of science content.

The processes of science

The strategies we have just mentioned are crucial for teaching students important NOS ideas. However, students can still cling to their misconceptions by discrediting these attempts and claiming that what has been occurring in class (e.g., black box activities) is not what real scientists do. Just as science teachers often use hands-on activities as evidence to convince students of science concepts, historical and contemporary episodes of science in action can serve as evidence to convince students of more accurate NOS ideas.

Many readings exist that directly target accurate portrayals of NOS. For example, at an appropriate time in the course, students can read portions of Peter Medawar's (1963) Is the scientific paper a fraud? Medawar illustrates how the systematic way investigations are conveyed in journals distorts how science research actually occurs. When showing science videos, teachers can punctuate these experiences with questions that explicitly draw students' attention to important points about NOS. For instance, in showing a videotape on genetics, genetic engineering, and the implications for society where one scientist compares doing science to composing music, teachers might stop the tape and ask, "How is doing science like composing music?" and follow that discussion with, "How is doing science different from composing music?"

Evidence for how science works is readily available in historical and contemporary examples tied to fundamental science ideas taught in particular subjects. Such examples (Abd-El-Khalick 1999; Clough 1997, 2004; Conant 1957; Hagen, Allchin, and Singer 1996; Klopfer and Cooley 1963; and Matthews 1994) illustrate the complexities and challenges scientists experience in constructing ideas and determining their fit with empirical evidence. Portions of the following works may be used to enhance students' understanding of science content and how science works: *The Double Helix* (Watson 1968) while teaching genetics, *A Revolution in the Earth Sciences* (Hallam 1973) when investigating continental drift and plate tectonics, *The Big Splash* (Frank 1990) when studying the origin of Earth's water, *Seeing Atoms* (Trefil 1990) and *For the First Time, You Can See Atoms* (Hoffmann 1993) when addressing atomic theory, and Nailing Down Gravity (Folger 2003). Figure 1 provides excerpts from a short story we developed illustrating how scientists' words can be used as evidence for important NOS ideas, and how questions are strategically placed to draw students' attention to such ideas. Teachers may integrate these stories alongside the introduction of science content or to illustrate how textbooks distort how science works. Integrating scientists' personal thoughts humanizes science and science education because it presents scientists as real people—with motives, prejudices, humor, and doubts—a view not always shared by students.

Figure 1. Three excerpts from an historical short story.

In the 1940s, most scientists thought that the genetic material would be made up of protein. Several reasons supported this contention. . . . However, work by Avery, MacLeod, and McCarty in 1944 was interpreted by many scientists to mean that deoxyribonucleic acid (DNA), not protein, was the genetic material. . . Not all scientists agreed with this interpretation of the evidence:

Of course there were scientists who thought the evidence favoring DNA was inconclusive and preferred to believe that genes were protein molecules. Francis (Crick) however, did not worry about these skeptics. Many were cantankerous fools who unfailingly backed the wrong horses. One could not be a successful scientist without realizing that, in contrast to the popular conceptions supported by newspapers and mothers of scientists, a goodly number of scientists are not only narrow-minded and dull, but also just stupid. (Watson 1968, 13).

However, Watson admitted that further experimental work was needed to show that all genes are composed of DNA. Additional evidence for DNA being the genetic material was reported by Hershey and Chase in 1952. . . . However, Watson and Crick (and other scientists) were already engaged in efforts to determine the structure of DNA before this work was reported, confident it was the genetic material.

Question: What does this disagreement among scientists imply about interpreting experimental data? What does this illustrate about how science works?

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Watson spent considerable time trying to make a like-with-like (i.e., cytosine paired with cytosine, guanine with guanine, thymine with thymine, and adenine with adenine) double stranded DNA structure work. However, he acknowledged that the difference in sizes between the pyrimidines and purines meant the sugar phosphate backbone would be quite irregular in width. Crick also noted that Watson's like-with-like idea did not account for Chargaff's rule (the amount of adenine in an organism equals the amount of thymine, and the amount of cytosine equals the amount of guanine). Interestingly, Watson professed not to have much faith in Chargaff's experimental work (Watson 1968, 112). Although Watson continued to work with his like-with-like idea, he eventually began entertaining other possibilities.

Question: Note that Watson did not give up easily on his earlier idea despite the evidence against it. Why might this be the case with him, or any scientist? What does this illustrate about individual scientist's objectivity?

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Later, while trying different arrangements of the purine and pyrimidine base pairs, Watson became aware that an adenine-thymine pair was identical in shape to a guanine-cytosine pair. He writes, "my morale skyrocketed, for I suspected that we now had the answer to the riddle of why the number of purine residues exactly equaled the number of pyrimidine residues. Chargaff's rule then suddenly stood out as a consequence of a double-helical structure for DNA" (Watson 1968, 114).

Question: Earlier Watson spoke poorly of scientists who did not accept the evidence for DNA being the genetic material. Yet Watson was resistant to accept Chargaff's experimental evidence. Why do you think Watson changed his mind about Chargaff's work? How does this story illustrate that scientific data does not tell scientists what to think?

Teachers must play an active role in posing questions at strategic points to explicitly draw students' attention to NOS ideas. Just as students rarely develop accurate science ideas from activities alone, accurate NOS ideas will not be learned simply by doing activities or reading/watching historical and contemporary accounts of science in action. While history of science and contemporary examples help create a credible case for NOS ideas, teachers are far too busy to dig through literature to create accurate stories of how fundamental science ideas came to be accepted. For this reason, we are working with historians of science, scientists, and secondary science teachers to develop short stories regarding historical and contemporary episodes tied to fundamental science ideas taught in secondary school biology, chemistry, physics, and Earth science. An example of these stories is found in Figure 1. Teachers interested in implementing full short stories in their classrooms and providing feedback are urged to contact the authors.

Telling the real story about science

Because NOS images are inextricably connected to science content and how it is presented to students, all science teachers and courses communicate a story to students about what science is, how science works, and other important issues about NOS. Teachers do not purposely teach mistaken ideas about NOS, but because they cannot escape teaching it, purposeful attention to the strategies suggested here is important. Teachers can be assured that their efforts to improve students' understanding of NOS will, over time, be successful.

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