Keys to Teaching the Nature of Science

William F. McComas, Guest Editor

Almost 20 years ago, Richard Duschl (1985) wrote an important essay reminding science teachers that the descriptions of "how science functions" typically provided in class and in textbooks had fallen out of step with the most accurate interpretations. Many cheered this article in hopes that, at last, one of the most important missing elements of science instruction would finally be addressed as accurately and completely as are the topics of plate tectonics in Earth science, mitosis in biology, pH in chemistry, and Newton's laws of motion in physics.

Unfortunately, the impact of Duschl's plea has been mixed. There has been a welcome proliferation of nature of science (NOS) elements and recommendations. Professional organizations including the National Science Teachers Association have issued position statements both advocating and defining relevant aspects of NOS (NSTA 2000). Increasing numbers of NOS standards appear in both United States (AAAS 1990, 1993) and foreign reform and standards documents (McComas and Olson 1998). The *National Science Education Standards* specifically includes standards focusing on science as a human endeavor and the nature and history of science across all grade levels (NRC 1996; 141, 170–171, 200–201).

These NOS recommendations are a step in the right direction. However, calls for the inclusion of NOS in science teaching have been made for almost a century (CASMT 1907) with frequent reminders during much of this time (Herron 1969; Kimball 1967; Robinson 1969; Duschl 1985; Matthews 1994; McComas, Clough, and Almazroa 1998; and Lederman 1992, 2002). The reality is that in spite of these continuous and well-reasoned recommendations, some students and teachers alike still fail to understand even the most basic elements of this important domain (Abd-El-Khalick and Lederman 2000). Studies show that a few teachers do not even value the inclusion of NOS elements in instruction (Bell, Lederman, and Abd-El-Khalick 1997).

A consensus of key NOS ideas appropriate for inclusion in the K–12 science curriculum has begun to emerge from a review by science educators of the extensive literature in the history and philosophy of science. The authors in this issue of *The Science Teacher* suggest surprisingly parallel sets of NOS content goals for K–12 science teaching that do not oversimplify science itself or overburden the existing science curriculum. This article presents nine key ideas, which represent both a concise set of ideas about science and a list of objectives to shape instruction in any science discipline.

Core NOS ideas

1) Science demands and relies on empirical evidence.

A hallmark of science is the requirement that data, open to review by others, be provided to justify all final conclusions. Of course, some ideas in science begin as exploratory notions; much of theoretical physics functions in just such a fashion. For example, Einstein's predictions about the impact of massive objects on the path of light were not dismissed outright due to lack of evidence, but neither were they accepted until evidence became available. In 1919, an expedition was mounted to test Einstein's prediction that the light of a distant star would be shifted slightly when it passed near the Sun. When the prediction was observed, a basic tenet of Einstein's new worldview was confirmed—with evidence. Although Einstein had faith in his assertion, the expedition data were needed for the rest of the scientific community to confirm the prediction.

The requirement for empirical evidence is accompanied by the caution that not all evidence is gained through experimental means, although that is frequently called the "gold standard" of science. In addition to experiments with their rigorous tests and controls, science also relies on basic observations (consider the work of Fossey, Goddall, and Galdikas as they

studied the great apes) and the historical explorations that have added so much to our understanding of the fossil record and geology generally. Many scientists use some combination of historical, observational, and experimental methods; the key point relating all of their investigations is the production and analysis of evidence in the form of data, measurements, photographs, meter readings, and other related observations. Despite its importance in other aspects of human affairs, faith alone in the correctness of one's views plays no final role in science. Science by its very nature is, and must remain, an empirical data-driven pursuit.

2) Knowledge production in science includes many common features and shared habits of mind. However, in spite of such commonalities there is no single step-by-step scientific method by which all science is done.

Although common features in the practice of science, like logical reasoning and careful data collection, are part of all good science, there is no universal set of steps that begin with "defining the problem," extend to "forming a hypothesis," "testing the hypothesis," and finish with "making conclusions" and "reporting results." Such a stepwise method commonly provided in science textbooks may be effective as a research tool, but there should be no implication in classroom discussions that all scientists use any single method routinely. In fact, studies of scientists at work reveal many idiosyncratic ways of approaching research and even of coming up with research problems in the first place.

3) Scientific knowledge is tentative but durable. This means that science cannot prove anything because the problem of induction makes "proof" impossible, but scientific conclusions are still valuable and long lasting because of the way that knowledge eventually comes to be accepted in science.

Induction is the knowledge generation process by which individual data points related to the problem or phenomenon are gathered until a general trend, principle, or law emerges from this mass of data. Prediction and deduction are used to evaluate the validity of the initial conclusion. This cycle of induction and deduction, a hallmark of logic, is far from perfect. There is simply no way to know that one has amassed all of the relevant data nor is there any way to be sure that the generalization suggested will hold true for all space and time. However, the logical knowledge generation process described briefly here is the best we have yet developed to provide ideas that are both useful and valid despite an inability to offer absolute proof. We can have confidence that scientific conclusions formed in this fashion will be long lasting or durable because of the

What Is NOS?

The definition and scope of NOS is quite basic; NOS is the sum total of the "rules of the game" leading to knowledge production and the evaluation of truth claims in the natural sciences. We have learned much about how science functions from reviewing its products, watching scientists at work, and viewing their interactions as a community. There is an entire domain of study called the social studies of science, which involves historians and philosophers of science along with sociologists who focus on scientists working in the laboratory, field, and in professional contexts. Even psychologists and physiologists interested in how human observations are made have helped shed light on aspects of the scientific enterprise. The work of these scholars has produced a description of how science functions from which we can derive a definition of NOS to inform the science curriculum.

Defining science and its mechanisms has become an important enterprise even for the courts. Following a charge from creationists regarding what could be discussed in science class, Judge William Overton (1985) in the case of *McClain vs. Arkansas Board of Education* synthesized the testimony of a variety of experts including Michael Ruse and Stephen Jay Gould. He wrote that science is guided by natural law and explains by references to natural law. It is tested against evidence from the empirical world and has conclusions that are tentative and potentially falsifiable. This focus on the "natural" is a key element of science. Science cannot delve into metaphysical questions and must rely on evidence gained from nature—either directly or through inference.

rigorous, self-correcting nature of the scientific process and the requirement that conclusions are agreed to by consensus of the scientific community.

4) Laws and theories are related but distinct kinds of scientific knowledge.

One of the most resilient misconceptions about science is that laws are mature theories and, as such, laws are more valuable or believable than are theories. Laws and theories are related but individually important kinds of scientific knowledge and both should be considered valuable products of the scientific endeavor. Laws are generalizations or patterns in nature (such as Charles's law), while theories are explanations for why such laws hold (such as the kinetic molecular theory of matter, which suggests that tiny particles behaving like billiard balls become more active as temperature rises). Many of the problems associated with evolution education arise when teachers fail to make the distinction between the reality that change through time has occurred (evolution with a law-like character) and the explanation for *how* evolution occurs provided by Darwin and Wallace (most accurately called the Theory of Evolution by Natural Selection). Those who understand the distinction between laws and theories would never call evolution "just a theory!"

5) Science is a highly creative endeavor.

Scientists, through their selection of problems and methods for investigation, would certainly agree that their work is creative. Even the spark of inspiration that leads from facts to conclusions is an immensely creative act. The knowledge generation process in science is as creative as anything in the arts, a point that would be made clearer to students who examine process as well as content.

Unfortunately, the average student is more likely to describe science as a dry set of facts and conclusions rather than a dynamic and exciting process that leads to new knowledge. In our quest to teach students what has already been discovered, we typically fail to provide sufficient insights into the true and *creative* NOS exploration. Some studies have shown that otherwise bright students reject science as a career choice simply because they have had no opportunity to see the creativity involved.

6) Science has a subjective element.

One of the little known aspects of science is that, because of its status as a human activity, it has a subjective component. Two scientists looking at the same data may "see" and respond to different things because of their prior experiences and expectations. This does not make science less rigorous or useful since ultimately the results will have to be discussed and defended before the larger scientific community. However, the initial discovery and analysis are ultimately personal and uniquely subjective events.

The prior insights that some scientists bring to the process of investigation explain why some individuals make monumental breakthroughs while others do not. Scientists recognize the role and challenges of subjectivity. Ideas and conclusions must be reviewed by other experts in meetings and through the publication peer review system. These processes ensure that the important subjective element in science is tempered by valid checks and balances.

7) There are historical, cultural, and social influences on science.

Science is a large and powerful enterprise that lies within the greater human social system. What research is performed and what research is discouraged or even prohibited is best understood by considering human forces such as history, religion, culture, and social priorities. Given the expense associated with scientific research, many would argue that scientists should consider only practical topics. In fact, there are societal pressures associated with certain domains of research. It should be no surprise that some kinds of research are favored and some are discouraged.

The debate regarding stem cell research and therapeutic human cloning is a current example of the interplay of science and cultural forces. Research directions such as these could be potentially fruitful and interesting, but for a variety of reasons extending far beyond science itself, these areas of research are presently controversial. Depending on the situation, it may be said that these social forces could either impede or support science. It may well be that Darwin's explanation of evolution by natural selection and the related notion of survival of the fittest could have been subtly suggested by the kind of ruthless capitalism Darwin saw around him.

8) Science and technology impact each other, but they are not the same.

Many confuse the terms *science* and *technology*, often considering them synonyms. Roughly speaking there are two kinds of problems investigated by modern science. Some problems relate to a particular need such as how to produce a more effective or less expensive music storage device, how to increase the agricultural yield of a plot of land, or how to vanquish a particular disease—all worthy endeavors. These challenges are technological in nature and represent what is frequently called "applied" science. On the other hand, "pure" science aims at basic understanding of the fundamental nature of reality sometimes called "knowledge for knowledge sake." Some of the discoveries of pure science, like the laser, were originally just curiosities until their utility later became apparent. Some technological innovations, such as the microscope, have provided scientists the ability to look more deeply into the ultimate nature of reality.

According to Weaver (1953, 47), "what science ought to be is what the ablest scientists really want to do;" however, the reality is far more complicated. Science and technology, and the cultural forces that surround them, are inexorably linked. Most times it is simply not possible for scientists to explore only in those directions that they find most interesting. Funding, as well as institutional and social priorities, simply do not typically permit what Weaver has advocated in the most pristine sense.

9) Science and its methods cannot answer all questions. One of the most important elements of NOS is for students to understand that limits exist to science and to appreciate that some questions simply cannot be investigated using scientific means. For instance, it may be possible to determine what percentage of the population likes a particular work of art, but it would be unreasonable to expect that science could fully explain why such an opinion exists. Such is also often the case with questions of morality, ethics, and faith—for many the domain of religion.

Knowing that science cannot and should not address all questions is vital if we are to avoid the common but false premise that science and religion are at war. To the contrary, science and religion play vital, but distinct, roles in human affairs. If only we could ensure that our students understand the distinction between reason and faith, science and religion, and the roles these two worldviews play in human affairs. In fact, an explicit focus on NOS as an integral part of the science curriculum would go a long way to accomplishing just such a goal.

The challenge before us is to ensure that these core NOS notions are featured prominently and explicitly in the science classroom, textbooks, in descriptions of how science functions, and in discussions of laboratory and other hands-on work. Even teacher-made final exams and new high-stakes tests should contain significant numbers of nature of science items, a state of affairs that would inform students and teachers alike of the importance of NOS as a focus of instruction. Finally, we must engage in the development of engaging curriculum models focusing on this important topic and insist that textbook authors weave NOS lessons through the content chapters instead of relegating it to the introduction, as is so often the case. NOS should be a central instructional purpose rather than an optional prelude. ■

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