FEATURE ARTICLE

# The Nature of Science & the Next Generation of Biology Education

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## Abstract

*The nature of science (NOS) is an often neglected part of science teaching, yet it provides a vital background for students, detailing how science and scientists work and how scientific knowledge is created, validated, and influenced. Here, I review the concept of NOS and some of the challenges to its inclusion in science classes. In addition, I outline proposals, including those in the Next Generation Science Standards, for those aspects of NOS that should be featured in science classes. Finally, I discuss distinctions in NOS specific to the science of biology and conclude with some thoughts on how NOS can be incorporated into science instruction.*

**Key Words:** *Nature of science; science teaching; philosophy of biology; Next Generation Science Standards.*

## ○ Introduction

This issue of *The American Biology Teacher* features articles related to the nature of science (NOS). This topic, of enduring interest within the science education community for more than a century, has been given a significant boost by its specific and detailed inclusion in the *Next Generation Science Standards* (NGSS), the new set of recommendations for science teaching in the United States. We at *ABT* are pleased to honor past interest in this important element of science instruction and herald a new future for NOS with this special issue.

Philosophers of science, historians of science, and science educators use the term "NOS" somewhat differently (Abd-El-Khalick et al., 1998), yet many would agree that NOS can reasonably be defined as "a rich description of what science is, how it works, how scientists operate as a social group and how society itself both directs and reacts to scientific endeavors" (McComas et al., 1998, p. 4). For more than 100 years, starting with recommendations from the Central Association of Science and Mathematics Teachers (1907) and continuing to the present (Lederman, 1992, 2007; Matthews, 1994, 2014; McComas, 1998, 2004), there has been increasing agreement that students and teachers alike must understand both the traditional science content and the "rules of the game" implied by the phrase "nature of science." Yet we have made surprisingly little progress convincing teachers and textbooks writers of the importance of this key learning goal.

> *This issue of* The American Biology Teacher *features articles related to the nature of science (NOS).*

## ○ Challenges to Inclusion of NOS in the Classroom

The inclusion of NOS in science teaching has not been without its issues, including discussions of NOS advocacy in science teaching, what version of NOS should be the focus of science instruction, distinctions in NOS between one science discipline and another, and NOS instructional models. These matters and more will be addressed in the next few pages.

### Advocating for the Inclusion of NOS in Science Teaching

One of the most important impediments to the inclusion of NOS topics in science teaching has been the rather muted recommendations regarding NOS in science curriculum documents. In the United States, each state has responsibility for determining the curriculum in each school discipline. This has resulted in a proliferation of state-specific curriculum documents. A detailed study (McComas et al., 2012) of all of these documents revealed that most states offered some recommendations regarding NOS, but the policies were highly variable. Some states had a robust section on NOS instruction and included all of the specific elements often suggested by

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science educators, whereas other states barely mentioned the topic. In the reality of the classroom, it is unclear how frequently NOS was featured in instruction or on teacher-made or state-mandated end-of-course tests. Such inclusion would encourage teachers to provide some instruction in NOS.

The NOS situation improved slightly with the development of Project 2061 (1989), the related *Benchmarks for Science Literacy* (AAAS, 1993), and the *National Science Education Standards* (NSES; National Research Council, 1996) which included some NOS recommendations. The NSES was an important document in that it was developed by a large group of experts and designed with the hope that states would adopt all or most of the recommendations. NSES generated much conversation but little concrete action, and states generally maintained their own science curriculum guidelines, although many were informed by aspects of the NSES.

The "standards movement" has recently reached a new level in science with the release of the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013). The NGSS were generated by representatives from a group of "lead states," with the goal that they be adopted wholly by those states and perhaps by many more. Since the 2013 release of the final NGSS document, there has been much debate, as each state is in a position to accept, reject, or modify the recommendations of the NGSS. It is clear that a majority of states will ultimately adopt the NGSS, making them a powerful tool for directing curriculum development, teacher preparation, and the design of shared assessments of educational progress. With widespread adoption of the recommendations provided in a single science education policy document, most students in the United States will be expected to learn the same science content. This is a historic moment in science education.

On first inspection, the NGSS offer three major recommendations to guide science teaching. These include (1) specific science content linked to grade levels; (2) crosscutting concepts (e.g., patterns, stability and change, structure and function) that link the sciences; and (3) shared science and engineering practices, such as asking questions, analyzing and interpreting data, arguing from evidence, and related ideas. In reality, the nature of science is a fourth major area advocated by NGSS that some might miss because of the way NOS is presented in the document. Unfortunately, the NOS recommendations do not have the prominence of the other three main NGSS elements, but finally there is a resounding voice of advocacy for NOS instruction. More about the specifics in a moment.

## What Nature of Science Should We Teach?

The NOS issue that has generated the most conversation is the specifics about what to teach regarding this important topic. In a recent article, van Dijk (2012) suggested that "at present, a general characterization of the nature of science is still lacking and probably such a characterization will not be achievable" (p. 2142). From a philosopher's perspective her statement is true at some level, but it is neither relevant to nor helpful in our discussions here. The position is not relevant because we are not trying to educate the next generation of philosophers of science, and not helpful because she offers no alternative and seems therefore to recommend that we continue teaching science without a reference to its nature.

In addition, one wonders what aspects of traditional science content would survive scrutiny if we evaluated all such content through van Dijk's lens. For instance, consider the ways in which photosynthesis can be taught. Students can become acquainted with photosynthesis by learning the inputs and outputs (a shallow treatment, to be sure). Or students can fully explore the biochemical pathways, electron transport mechanisms, and fine detail of chloroplast structure and chlorophyll function. Most would argue that there is nothing wrong with the introductory view as long as it is essentially accurate. In this example, communicating the inputs and outputs of photosynthesis to students is certainly not incorrect, but it is not complete. However, such an introduction may afford students sufficient knowledge to be interested in learning more, perhaps through an AP Biology class or a semester-long botanical bioenergetics class at the university level, where the fascinating nature of photosynthesis can be fully investigated. The argument that the science education version of NOS is not complete or rich enough seems faulty unless those who offer it are prepared to attack all school science content as equally incomplete or shallow.

Finally, we can see that van Dijk's argument is simply not helpful in that she proposes no alternative. She apparently fails to see that for most students, the school science experience is an introduction, not the final word on what we know about the natural world. Certainly, what we teach in science class must be accurate, but must it also be perfectly complete?

In recent decades, numerous recommendations have been offered for what NOS elements, aspects, or categories are most appropriate to enrich science instruction. Those by Lederman (2002, 2007); McComas (1998, 2004, 2008); and Osborne et al. (2003) align nicely with those in the NGSS. The approach of examining sets of recommendations for their common elements is called the "NOS consensus approach" and has been profitable in providing guidance regarding the element of NOS that might be integrated into science teaching.

The NOS recommendations in the NGSS are derived from this consensus perspective and are presented in an appendix and in two detailed tables, one linked to the practices of science (Categories I–IV) and another related to the crosscutting concepts (Categories V–VIII). The following is a list of the eight NOS categories in the NGSS.

I: Scientific Investigations Use a Variety of Methods
II: Scientific Knowledge Is Based on Empirical Evidence
III: Scientific Knowledge Is Open to Revision in Light of New Evidence
IV: Science Models, Laws, Mechanisms, and Theories Explain Natural Phenomena
V: Science Is a Way of Knowing
VI: Scientific Knowledge Assumes an Order and Consistency in Natural Systems
VII: Science Is a Human Endeavor
VIII: Science Addresses Questions about the Natural and Material World

Each of these categories is accompanied by illustrations that provide additional commentary, and many of these illustrations are further associated with the recommended science content, crosscutting concepts, and science and engineering practices.

There is much more good news than bad about NOS in the NGSS. However, some of the frequently recommended NOS elements, such as the role of creativity and subjectivity in science, are either missing entirely or hidden within the NOS illustrations,

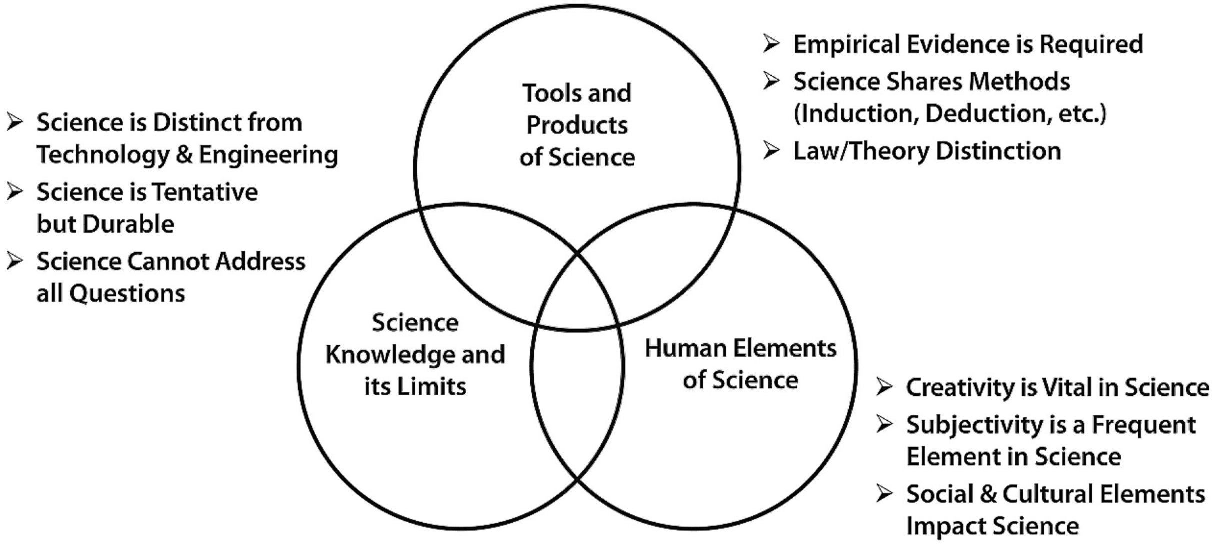

**Figure 1.** The major elements of NOS appropriate for inclusion in science instruction, arranged in three related clusters (modified from McComas, 2008).

making a complete statement on what NOS to teach somewhat difficult for teachers to find. One of the NOS categories, "Science Is a Way of Knowing," seems unnecessarily vague; what does one teach to focus on this statement?

## NOS for School Science Purposes: Beyond the *Next Generation Standards*

There is likely no list of NOS elements that all science educators would embrace, but some might see the conceptualization offered by McComas (2008) as a clear and comprehensive representation of NOS for school purposes. It is not possible to provide a full description of each of the recommended NOS elements here, but such a discussion can be found in McComas (2004, 2015). One can gain a reasonable overview by examining Figure 1 and the corresponding outline below, in which the nine elements are organized in three clusters.

### *Outline of Proposed Core NOS Ideas to Inform K–12 Science Curriculum Development, Instruction, & Science Teacher Education*

**Note:** An asterisk indicates that the particular NOS idea is found in or implied by the NGSS (in appendix H and the associated illustrations). On this point, consider that the NOS principle that "science cannot answer all questions" is implied by the NGSS statement that "science addresses questions about the natural and material world." This would seem to suggest that science does not address questions that do not pertain to the natural and/or material world; thus, there are limits to science.

*Tools and Products of Science*

(1)* Science produces, demands, and relies on empirical evidence.

(2)* Knowledge production in science shares many common factors and shared habits of mind, norms, logical thinking, and methods, such as careful observation, careful data recording, and truthfulness in reporting. The shared aspects of scientific methodology include the following:

- Experiments are a route, but not the only route, to knowledge.
- Science uses both inductive reasoning and hypothetico-deductive testing.
- Scientists make observations and produce inferences.
- There is no single stepwise scientific method by which all science is done.

(3)* Laws and theories are related but distinct kinds of scientific knowledge.

*Human Elements of Science*

(4)* Science has a creative component.

(5) Observations, ideas, and conclusions in science are not entirely objective. This subjective (sometimes called "theory-laden") aspect of science plays both positive and negative roles in scientific investigation.

(6)* Historical, cultural, and social factors influence the practice and direction of science. The topics of scientific inquiry are as much dictated – through funding and focus – by the needs of a particular society as they are by the curiosity of scientists.

*Science Knowledge and Its Limits*

(7) Science and engineering/technology influence each other but are not the same.

(8)* Scientific knowledge is tentative, durable, and self-correcting. (This means that science cannot prove anything, but scientific conclusions are valuable and long-lasting because of the way in which they are developed; mistakes will be discovered and corrected as part of the process.)

(9)* Science and its methods cannot answer all questions. In other words, there are limits to the kinds of questions that may be asked within a scientific framework.

Much has been written – both pro and con – about "lists" such as those provided above, in the NGSS, and in various contributions to the literature. Those who support the contents of such lists are motivated not so much by a desire to present a full account of the history and/or philosophy of science, but more by the hope that students will learn something about how science functions by exploring what might best be called "NOS-for-school-purposes." This is exactly the same goal as that of biochemistry-for-school-purposes, or photosynthesis, or taxonomy, or any other goal associated with the school science experience.

### The Nature of Science across the Boundaries of the Sciences

Another criticism occasionally offered regarding NOS recommendations is that the nature of science does not function across the sciences in exactly the same fashion. For example, van Dijk (2011, p. 1086) states that the lists ignore "the actual heterogeneity of science" and questions "whether such consensus views can fruitfully contribute to the aim of science communication, i.e., to enhance the public's functional scientific literacy." There is some validity in this statement regarding the notion that the rules of the game of science operate somewhat differently in one science compared with another. However, are these differences so substantive as to derail attempts to look for commonality across the sciences? Philosopher of science Elliott Sober (2015) states that the answer is "No." While he recognizes the various perspectives on this issue, he has concluded that "there are general normative principles that govern every science" (p. 195). Sober's pragmatic perspective is shared by those who advocate the development of a generalized view of science designed specifically to inform the teaching of all sciences.

From the "big picture" perspective of how science works, there is far more in common between the sciences than not, and it is possible to provide some general normative practices worthy of discussion in all science classes. Even if we acknowledge some distinctions based on the context of a specific science discipline, from a pedagogical perspective it would make no sense to focus on the small differences in NOS if students fail to see the big transcendent ideas. We want students to know that scientific conclusions are based on evidence, that scientific ideas are potentially revised with new evidence, that science is a human endeavor, that science is limited to exploring aspects of the natural world, that creativity plays a role in all aspects of science, and that there is a distinction between the goals of science and those of engineering.

## ○ Aspects of the Nature of Biology: A *Very* Brief Consideration

This next section is offered with a measure of fear and enthusiasm. I am fearful to offer anything that, of necessity, will be much too brief. Interested readers will be better served by consulting any of the much more comprehensive books written on the philosophy of biology by experts such as Sober, Rosenberg, Ruse, and Mayr, among others. However, this brief introduction is designed to start the conversation about distinctions in the way that NOS functions in the science of biology. Once teachers and students have come to understand the general foundational notions that guide the practice of science, a consideration of the philosophy of biology is an interesting and worthy pursuit.

A study of the philosophy of biology could start with a conversation that many science teachers have on the first day of class. The exchange usually begins with the question, likely rhetorical: What is biology (or chemistry or physics)? This is a deeply philosophical question. It is vital that students understand exactly what defines and limits the science they will study in each science class. In biology this seems easy: biology is the study of life. Yet the discipline of biology is focused on the chemicals of life, the interactions of living things with the nonliving environment, and, most interestingly, entities at the margin of life, such as viruses. Moments after some list of the "characteristics of life" is presented in a lecture or textbook, viruses might be offered as an exception to the rule. Examples such as this are perfect challenges to the preconceptions that many students hold about the characteristics of the living world.

With respect to the central question in biology, we find – in two books on the philosophy of biology separated by decades (Ruse, 1998; Kampourakis, 2013) – the same question: "What is life?" There is little more fundamental to the biological sciences than the answer to this query. Among those who first asked it was physicist Erwin Schrödinger, in his book *What Is Life?* (1946). He defined the distinctiveness of the science of biology by stating that living matter works "in a manner that cannot be reduced to the ordinary laws of physics" (p. 81). "The unfolding of events in the life cycle of an organism exhibits an admirable regularity and orderliness unrivaled by anything we meet with in inanimate matter" (p. 82). His book inspired Watson and Crick and others among the first generation of molecular biologists to consider the life sciences from a new perspective.

Of course, there are many interesting philosophical aspects of the life sciences. In the next few pages, we will consider just four: the issues of reductionism, typology, determinism, and universality. Any of these could provide interesting fodder for classroom discussion.

*Reductionism* is the idea that you can best understand the whole by understanding the parts of the whole. Reductionism plays some role in all the sciences but is particularly interesting in biology because the unit (i.e. the organism) functions as more than the sum of its parts. As an example, consider the statement of Smith (1986) that "Mendel's discovery of the laws of heredity…could not at that time (or ever?) have been deduced from molecular biology, but which have since been explained in those terms" (p. vi). Further, he states that we have learned much by looking at the parts but "there are laws that can only be discovered by research on whole organisms or populations of organisms" (p. vii).

The current trend of "systems biology" notwithstanding, recent history has shown a reductionist mindset when it comes to biology. It might be useful to consider whether this is good or bad for science and for humanity. Increasingly, we see ecology programs downsized and molecular biology programs growing in personnel and funding. Good old-fashioned natural history is generally out, and the study of parts of genes is in. From a fiscal perspective, this makes sense. There is money available for study, and the prospect of product development exists in molecular biology to a far greater degree than in studying the Arctic food web of polar bears. But can we understand polar bears by only studying their DNA? Or, to look at it another way, what do we lose by examining the part of a strand of nucleic acid and not a food web? Lange (2013, p. 84) states the case well: "Even if we could study [organisms, populations, communities, and ecosystems at the molecular level] we should not do so. That is because we would thereby miss out on distinctive ways of understanding biological phenomena."

*Typology* is likely a term never mentioned in the typical biology class, but this concept should play a role in biology instruction or students might question why there is no "periodic table of the animals." Typology, or Platonism (named for Plato, who developed the notion of "type"), is the notion that one can take a representative of a group of similar things, study that, and know about all those in the group. Excluding the notion of isotopes, when one learns about the element carbon, for instance, one comes to know much about all carbon atoms. This is not the case in biology. Individual differences, even among representatives of the same species, can be pronounced. For centuries, we have defined a "type species" and used that to represent all others, but it could be enlightening to consider just how useful this concept is.

The issue of "type" features in medicine even at the level of the sexes. Doctors now recognize the basic truth that treating women on the basis of research on men makes little sense. We will undoubtedly see an increase in the practice of "personalized medicine," which generally abandons the idea of "type" in favor of the individual. Personalized treatments are recommended to individuals on the basis of knowledge of their particular genetics and/or biochemistry; the days are waning when everyone with the same illness is treated in the same fashion. In chemistry and physics, it is possible to profit from a typological perspective, but the science of biology is too complex for that.

*Determinism* is associated with the "clockwork" universe of Newtonian physics. That notion asserts that once we know all the rules governing a system and understand the initial conditions, it is possible to predict the future state of affairs with some accuracy. Perhaps no science is fully confident that this holds true, but in biology it will certainly remain a suspect notion. The vagaries and complexities of individuals, the interactions of groups of individuals with others and with the environment, all in a setting of both biological and physical evolution, make useful prediction impossible. Although one might expect to make useful (i.e., highly specific) long-term predictions in chemistry and physics, few biologists would be so bold. For instance, biology is based on evolution as its underlying principle, yet although we know that living things evolve, it is impossible to predict with any precision what form that evolution will take.

*Universality* suggests that the scientific generalizations and explanations garnered here on Earth hold true everywhere. This is a very strong (and useful) assumption in chemistry and physics, but perhaps somewhat suspect in biology. When light from a distant star is analyzed and reveals the presence of a particular suite of elements, astronomers assume that the chemical signature implied by an analysis of the light spectrum tells us the same thing about some far-away stellar object as it would if that light were produced in an earthbound laboratory. There is a strong assumption that the rules of physics and chemistry operate elsewhere as they do here. But what about biology?

Unless one believes that the government has been studying alien (i.e., not-of-this-world alien) life-forms in some secret laboratory, earthbound scientists have never examined anything living from beyond terra firma. Everything we know about life, we know from looking at the living representatives of our planet only. Even our probes designed to find life elsewhere, such as on Mars, are based on what life looks like here. All definitions and descriptions of life are linked to only one planet. We expect that life has developed elsewhere, we expect that water must play as strong a role in living systems on other planets, we expect that there must be some form of evolution beyond our planet – but we just don't know.

Students find such conversations intriguing, and so do science fiction writers. A *Star Trek* episode, "The Devil in the Dark," featured a life-form based on silicon rather than carbon. Why not? Silicon has many of the same properties as carbon and thus reacts in much the same way. Who is to say that life must be based on carbon?

To conclude this section on universality, we will consider laws and theories and how they operate in biology, as a useful comparison with the way things work in the physical sciences. Theories and laws are different kinds of knowledge, but they are often portrayed as hierarchical, with laws being more valuable. That is not true. Laws are generalizations (usually said to have been discovered) about some aspect of nature, and theories are the explanations (usually said to have been invented) for why those laws hold (Campbell, 1953; Horner & Rubba, 1978, 1979; Rhodes & Schaible, 1989).

Laws make statements about instances, such that one could say that since all reptiles have scales, the reason that my pet snake has scales is because of the "reptile principle," a part of which is that "all reptiles have scales." Some might say that there is a law of reptiles because the generalization (all the things we know about reptiles) is well established and useful in making predictions.

Theories, on the other hand, explain why laws hold true. A wonderful example of this is the Darwin/Wallace theory of evolution by natural selection. If the theory of natural selection, and related notions such as common descent, explain how evolution occurs, and if theories explain laws, it is reasonable to say that the principle of evolution itself is law-like. Some may have a problem considering the principle of evolution a law, but it certainly seems to operate in that fashion. Of course, the predictions that one can make simply by saying that living things evolve are less certain than predictions provided by laws in the physical sciences. However, knowing that living things evolve seems enough to give the fact, or generalization, of evolution something close to law-like status.

Laws are explained by theories but can themselves be used to explain instances. So, if one goes to the Grand Canyon and notes the progression of fossils in the rocks (from less complicated life-forms deep in the rock layer to more complicated and "modern" higher up in the younger rocks), it is reasonable to ask two questions: "Why are the fossils the way they are in the rock layers?" and "How did this happen?"

Even if one had no idea of a mechanism, the realization that a process called "evolution" was responsible for the pattern in the rocks would be a reasonable explanation for this instance. Most people would not find it very satisfying to continually say that evolution as a principle is responsible for this and that, so the quest to find the mechanism was inevitable. This is the landmark contribution from Darwin and Wallace. In great measure, it is natural selection and related processes like descent that tell us *how* this process called "evolution" functions.

Evolution is a fact and approaches law-like character when used to explain instances, whereas the explanation called "natural selection" is most certainly a theory. Students must recognize the distinction between "evolution as principle" and "evolution explained in part by natural selection." Inclusion of NOS in science instruction and some focused attention on the matter by teachers may allow us to put an end to the incorrect and useless sentence "Evolution is only a theory."

One major distinction between the functioning of laws in biology and in other sciences concerns the expectation of generalizability. One who expects a "law" in biology to apply 100% of the time will be disappointed often. Consider the example of Bergmann's (body) rule and Allen's (appendage) rule. These generalizations state that animals near the poles will have stubbier appendages and more rotund bodies (i.e., less surface area) than animals near the equator.

In fact, these body rules hold true for approximately 70% of animal species studied. That's not 100%, and perhaps this is why we do not talk about laws in biology nearly as much as in other sciences – although, at the casino, 70% odds is better than even money any day. Betting that a new polar animal will be stubby and rotund is relatively safe, but "laws" in biology can be problematic if you expect perfection. Even though laws in chemistry and physics come much closer to 100% applicability, we can still have laws in the life sciences by keeping in mind that a biological law and a physical law are somewhat different.

Sober (2015) reminds us that, from a NOS perspective, biology has much in common with the physical sciences. All of the NOS ideas in the NGSS apply across all the sciences, in spite of the issues about universality, typology, determinism, and reductionism discussed here. As a biologist, I would argue that these special cases make the science of biology more interesting, more integrated, and more dynamic than what some like to call the "hard sciences."

## ○ The Future of NOS Instruction

Half a century of research into NOS in school science has provided a clear picture of what teachers and students know about the subject and how NOS might best be integrated into science instruction. As summarized by Lederman (2007), research studies suggest the following:

- K–12 students do not typically possess "adequate" conceptions of NOS.
- K–12 teachers do not typically possess "adequate" conceptions of NOS.
- Teachers' conceptions of NOS are not automatically and necessarily translated into classroom practice.
- Teachers do not regard NOS as highly as they do "traditional" subject matter as a worthy outcome of science instruction.
- Conceptions of NOS are best learned through explicit, reflective instruction, as opposed to learning implicitly through experiences with simply "doing" science.

With the advent of the *Next Generation Science Standards*, we can add to this list. We now know that NOS is an instructional goal equal to that of traditional science content, and we know what NOS aspects our teaching should focus on. So what happens next?

First, teachers must develop what Abd-El-Khalick and Lederman (2000) call "NOS Pedagogical Content Knowledge (PCK)." Like other forms of PCK, NOS-PCK implies that in order for science teachers to integrate NOS in their classrooms, they must possess appropriate knowledge of NOS and must learn or develop the pedagogical tools related to teaching the fundamental aspects of NOS. Science teachers must develop

> deep, robust, and integrated NOS understandings so that they can convey to students images of science and scientific practice that are commensurate with historical, philosophical, sociological, and psychological scholarship (teaching about NOS), but structure robust inquiry learning environments that approximate authentic scientific practice, and implement effective pedagogical approaches that share a lot of the characteristics of best science teaching practices (teaching with NOS). (Abd-El-Khalick, 2013, p. 2087)

We also know that what teachers understand about NOS influences their beliefs about teaching it (Waters-Adams, 2006), so every science teacher must have deep personal knowledge about the main elements of NOS if they are to effectively integrate it into their science lessons. We also know that for teachers and students, memorizing some list of NOS aspects is not the appropriate approach. Unfortunately, many of those who reject the consensus approach criticize it by suggesting that its content is designed to be memorized. Allchin (2011, p. 523) stated that "there is yet no evidence that mere recall or comprehension of such NOS tenets is adequate for applying them effectively in context. . . ." Such a conclusion is not at all surprising, because no NOS proponent advises such a cursory interaction with the nature of science.

Think of the NOS elements as destinations and now the goal is to determine how best to take the journey to get there. For instance, it is one thing to tell students that knowledge in science has a subjective component and that sometimes prior understanding can block the ability to "see" unanticipated results. It is far more effective to point out this phenomenon when the opportunity presents itself in the context of discussing traditional science content, or even design a laboratory lesson in which students see this for themselves. This can only happen, as Waters-Adams (2006) points out, when teachers are prepared.

Preparing a lecture or two on NOS at the beginning of the year and never mentioning it again is also *not* recommended. It is most effective to integrate NOS into science lessons explicitly and contextually. Teachers should look for places in existing content lessons where NOS could be introduced. During lecture/discussion, NOS may be exemplified using historical anecdotes (for more on this approach, see McComas & Kampourakis, 2015). The history of biology is rich with instances and personalities to help illustrate aspects of NOS. For instance, the creative aspect of science can be neatly shown by exploring how Darwin used artificial selection in pigeons, which he could observe in real time as a stand-in for the mostly imperceptible process of natural selection. Needless to say, teachers must know these stories before they can integrate them into instruction.

The laboratory, too, is a wonderful place to help students see how science works. If a knowledgeable teacher engages students in activities that feature reasonable levels of inquiry, this will go far in assisting their NOS understanding, particularly when these teachers are poised to point out the NOS lessons that can be learned while the investigation proceeds.

In brief, teachers must have reasonable levels of NOS knowledge and a commitment to teach it along with traditional science content. NOS lessons must be woven into existing lessons through inquiry, stories, and explicit instruction throughout the school year and by making reference to the specific biological content being explored. The time is right for a NOS instructional revolution. We now have the *Next Generation Science Standards* providing support and recommendations for what NOS aspects to teach, and the call is strong to focus the curriculum more on modes of knowledge generation in science, not just on the knowledge itself. Given the strong interest that students generally have in biology and its status and the most commonly taught secondary-school science class, Biology is the perfect environment for students to learn science while learning how science works.

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