Current reform documents place a strong emphasis on students’ understandings of the nature of science (NOS) (AAAS 1990, 1993; NRC 1996). Interestingly, the importance of this educational outcome is not new and has been agreed upon as important by most scientists and science educators for the past 100 years (CASMT 1907; Kimball 1967–1968; Lederman 1992). Despite numerous attempts, including the major curricular reform efforts of the 1960s, to improve students’ views of the scientific endeavor, students have consistently been shown to possess inadequate understandings of several aspects of NOS (Aikenhead 1973; Lederman 1992; Lederman and Abd-El-Khalick 1998; Lederman and O’Malley 1990; Mackay 1971; Mead and Metraux 1957; Rubba and Andersen 1978; and Wilson 1954).

The reason for this problem is twofold. First, there is much confusion about NOS (it is often confused with inquiry) and second, there are few research-based resources available to teachers to facilitate the teaching of NOS. Our purpose here is to offer some suggestions on both fronts. A good start would be to clarify what we, and others, mean by NOS.

**What Is NOS?**

The phrase *nature of science* typically refers to the values and assumptions inherent to scientific knowledge and the development of scientific knowledge. Although there are disagreements about specific aspects of NOS, we have chosen to focus on seven
aspects that are generally agreed upon, accessible to K–12 students, and important for all citizens to know.

First, students should be aware of the crucial distinction between observation and inference. Observations are descriptive statements about natural phenomena that are “directly” accessible to the senses (or extensions of the senses) and about which several observers can reach consensus with relative ease. For example, objects released above ground level tend to fall and hit the ground. By contrast, inferences are statements about phenomena that are not “directly” accessible to the senses. For example, objects tend to fall to the ground because of “gravity.” The notion of gravity is inferential in the sense that it can only be accessed and/or measured through its manifestations or effects. Discussions about gravitational forces being responsible are largely inferential.

Second, closely related to the distinction between observations and inferences is the distinction between scientific laws and theories. Laws are statements or descriptions of the relationships among observable phenomena. Boyle’s law, which relates the pressure of a gas to its volume at a constant temperature, is a case in point. Theories, by contrast, are inferred explanations for observable phenomena. The kinetic molecular theory, which explains Boyle’s law, is one example. Theories and laws are both very important to science and they are different types of knowledge. Theories do not mature into laws.

Third, all scientific knowledge is, at least partially, based on and/or derived from observations of the natural world. All of the theories and laws developed by scientists must be checked against what actually occurs in the natural world.

Fourth, although scientific knowledge is empirically based, it nevertheless involves human imagination and creativity. Science involves the invention of explanations and this requires a great deal of creativity by scientists. This aspect of science, coupled with its inferential nature, entails that scientific concepts, such as atoms, black holes, and species, are functional theoretical models rather than faithful copies of reality. All “inventions” are not equally appropriate. When scientists construct knowledge by making inferences from observed data, their inferences must be consistent with the natural world as well as the current knowledge base in science. Scientists are not free to speculate without any constraints.

Fifth, scientific knowledge is at least partially subjective. “Subjectivity” in relation to scientific knowledge refers to the influence of accepted theories in the scientific community as well as the individual backgrounds of researchers. The key point is that scientists do not collect and interpret data without preconceptions and biases. Scientists’ theoretical commitments, beliefs, previous knowledge, training, experiences, and expectations actually influence their work. All these background factors form a mind-set that affects the problems scientists investigate and how they conduct their investigations, what they observe (and do not observe), and how they interpret their observations.

Sixth, science affects and is affected by the various elements and contexts of the culture in which it is practiced. These elements include social fabric, power structures, politics, socioeconomic factors, philosophy, religion, and other factors. In short, we say that science is socially and culturally embedded.

Seventh, it follows from the previous discussions that scientific knowledge is subject to change. This knowledge, including “facts,” theories, and laws, is tentative and subject to change. Scientific claims change as new evidence, made possible through advances in theory and technology, is brought to bear on existing theories or laws, or as old evidence is reinterpreted in the light of new theoretical advances or shifts in the directions of established research programs.

**Teaching NOS**

Almost any science activity can be modified to explicitly teach some aspects of NOS, without much effort, loss of class time, or loss of attention to important subject matter. We will first describe a popular laboratory activity that is widely used by biology teachers and is seemingly as far removed from NOS as anyone could imagine. Then, we will present the same activity restructured to help students learn about NOS.

**Time for Mitosis**

The following activity is found in virtually every high school biology laboratory manual. The primary goal of the activity is for students to learn the relative amounts of time required for each of the stages of mitosis and the remainder of the cell cycle. Other goals are for students to become adept at identifying the stages of mitosis and to realize that cell division and growth is much quicker in cancerous cells than in normal cells. Following a brief review of the different stages of the cell cycle and how to categorize stages from pictures, students, usually in at least pairs, are asked to count the number of allium (onion) root tip cells (on a prepared slide) in each stage of mitosis within a given field of view under high power. They are asked to do this for three fields of view. After the counts are entered on a data table, students use the relative frequencies of stages to calculate the relative time required for each stage.

The cell cycle takes an average of about 24 hours (1440
minutes) in onion cells, so students use the frequencies to calculate proportions of time. The assumption is that the stage with the fewest numbers counted takes the shortest time. The activity is fairly reliable in having students conclude that the shortest to longest stages in order are: anaphase, telophase, metaphase, prophase, and interphase. Students are then shown a table of data comparing the time requirements for each mitosis stage in normal and cancerous cells from a chicken’s stomach. Through a series of review questions, students are led to the general conclusion that mitosis occurs much more rapidly in cancerous cells. They are also led to the general conclusion that the relative time requirements for each mitosis stage in normal and cancerous cells are the same in all organisms. This latter conclusion is more implied than explicitly stated.

**Time for Mitosis: Focus on Nature of Science**

This activity as typically presented may be straightforward and somewhat uninteresting, but it does help students learn some foundational knowledge about mitosis and the cell cycle. Mitosis and the indicators of its stages are core concepts in most biology textbooks and curricula (Figure 1). So, is it possible to help students learn about NOS during this activity without corrupting the activity to the point that learning of the original subject matter is compromised? The various aspects of NOS previously discussed are not something that students will directly see in the mitosis activity or any other activity. Rather, NOS becomes visible through the careful use of reflective questions. At the beginning of the activity, when students are given a brief review of the stages of mitosis and the cell cycle, you could ask, “How do we decide when one stage ends and the other begins?” “How did scientists decide?” Responses will quickly lead to the arbitrariness of the categorization of stages (as is true of any classification scheme in any discipline). At this point, you can bring up the subjectivity involved in such decisions as well as the possibility that categorizations may change in the future as a result of more knowledge about mitosis or scientists simply deciding that it makes more sense to “segment” the process in a different way.

During the few practice examples that students do as a class before starting to work in groups, be sure to ask about the stage of a cell that is not totally clear, an unclear exemplar. Have the students defend their differences in how they classified this particular cell. Use this discussion to explicitly talk about the judgment call they made and ask, “Why did you classify the cells differently?” Be sure to stress that there is no precisely correct answer. People with differing backgrounds, perspectives, and knowledge will likely reach different conclusions because of different interpretations. The point to be made is that subjectivity has unavoidably been involved. The same is true among scientists when they interpret data.

Following the collection of data during the laboratory, ask students why different groups came up with different frequencies and calculated times. If groups do not agree on the overall relative times across stages, it is even better. Again, you can explicitly stress that different students and groups interpreted the data in different ways. You can also discuss whether all groups observed the root tips in the exact same location. And, what about the implications of each group collecting data from a different sample? Students’ answers to these questions will allow you or them to stress how scientific knowledge is tentative and involves subjectivity.

You can also choose to focus on the idea that students were making observations with their microscopes and using these observations to make inferences about the relative time requirements for each stage (naturally, this would be a good time to quickly have students reiterate their understandings of the difference between observations and inferences). After all, only snapshots of the process are being viewed with no one timing each stage.

So, you may also now ask, “Can we be totally sure that the relative time requirements we have determined are correct?” Students should quickly realize that what has been concluded may change with additional data, different samples, or different frameworks for determining stages of mitosis. At this point in the lesson we have been able to ask questions that allow students to reflect on the following aspects of NOS: tentativeness, subjectivity, observation vs. inference. Naturally, at any point in the lesson you could raise the issue that students are attempting to answer their question as scientists do, not from just thinking about the situation, but rather from the collection of empirical data. Scientific knowledge, they need to remind themselves (with your help), is at least partially based on empirical data.

During the review of the activity, you can ask students if
the relative time requirements for the stages are the same in animals and plants, using the chicken and onion examples studied. Is there any reason to believe that the stages are relatively the same, but not exactly the same? Are students making inferences? What are their inferences based upon? How can students find an answer? Finally, during the debrief of the data comparison of cancerous and normal cells, ask students to speculate about why cancerous cell activity is a problem. After all, what’s so bad about the cell cycle occurring at a faster than normal rate? Students’ answers will be inferences and this will allow you to stress that scientists’ inferences are a product of human subjectivity and human creativity. If you have the urge, you can even ask, “Is it okay to make conclusions about cancer in general from data of cancerous chicken stomach cells?” This can lead to a discussion of the inferences that medical scientists make when doing clinical trials with organisms that serve as human models.

A striking difference

A comparison of the two different approaches to the mitosis lab should make clear at least one striking difference. The second approach integrated certain aspects of NOS through discussions initiated with carefully selected and placed reflective questions. In this case, it was determined that tentativeness, creativity, observation/inference, subjectivity, and empirical basis were the best fit for the lesson at hand. The difference between theory and law and the cultural embeddedness of scientific knowledge were not as easily approached through this activity. All aspects of NOS need not, and should not, be addressed in every lesson or activity. Focusing on a few aspects that best fit the lesson at hand is much better.

Some students might independently reflect on what they are doing and come to understand NOS through the performance of the original activity. However, research is quite clear that most students do not learn NOS implicitly, simply by doing science activities. Rather, the aspects of NOS you wish to emphasize need to be planned for and explicitly integrated into the lesson. The best way to do this is through reflective discussions elicited through careful questioning.

We cannot overemphasize the importance of taking time, during and at the conclusion of any activity, to explicitly point out to students the aspects of NOS that are highlighted. Initially, you may need to be more directive, but as time goes by you should be able to more easily elicit discussions about NOS from your students. To encourage reflection, teachers must discuss with students the implications such aspects of NOS have for the way they view scientists, scientific knowledge, and the practice of science.

We should not assume that students will come to understand NOS as a by-product of “doing” science-based or inquiry activities. If secondary students are expected to develop more adequate conceptions of NOS and scientific inquiry, then, as any cognitive objective, this outcome should be planned for, explicitly taught, and assessed. In addition, it should be clear that NOS activities do not need to be created from scratch. All that is needed is the placement of some carefully planned questions within the activities that you are already doing. If the activity is a science activity, then it contains NOS below the surface. Your questions and subsequent discussions bring NOS to the surface and promote student learning of both the original subject matter and the aspects of NOS you have chosen to emphasize.

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