Science, Engineering, and Technology

What distinguishes science from engineering and technology? In general, science can be thought of as a study of the properties and interactions of matter and energy (physics), of atomic reactions and changes (chemistry), and living and interacting systems (biological and environmental sciences). According to *Science for All Americans*, engineering can be thought of as "a systematic application of scientific knowledge in developing and applying technology" (AAAS, 1989, p. 26). The primary distinguishing characteristic of science and engineering is the difference in the perceived goal of the work. Paraphrasing the *National Science Education Standards* (NRC, 1996, p. 24), the goal of science is to understand the natural world, and the goal of engineering is to apply the knowledge of science to make modifications in the world to meet human needs. Science provides a method for approximating what behavior or performance a device will have before it is made and observed. Engineering deals with the applications of mathematics and the sciences to the design and development of useful items—the result of which is known as technology. This technology helps society and the individual to control, change, and take charge of the natural world and make it suit our needs. Technology provides us with basic necessities such as clean drinking water, safe food, shelter, medical care, and defense.

Technology is strongly dependent upon science, but science also relies strongly upon technology. To a great extent, various technologies have become the hands, voices, and senses of scientists and society. For instance, robots now do a large amount of detailed and precise assembly work and handle hazardous materials and search the bottom of the ocean. Computers have allowed us to study demographic patterns, solve mathematical problems, work out the human genome, model complex systems, and simulate situations that might be too difficult or expensive to produce. Space satellites have allowed us to set up global communication, data relay, and global positioning system networks. None of this would have been possible without the development and deployment of miniaturized electrical circuits.

Many advances in science have been made as a result of the development of new technology. For instance, scientific instruments such as the telescope, the microscope, and satellites have made further advances in the fields of astronomy, biology, and meteorology possible. At the same time, technology has—in some cases—come to pose a threat to our very existence. Such is the case with weapons of mass destruction, and our ability to produce environmental pollutants. Technology is a double-edged sword that can have unforeseen benefits and unexpected risks and consequences for different people, places, and times.

Society depends strongly upon technology. The quality of life has improved in many areas of the world as a result of technology that is now a common part of everyday life: personal computers, light bulbs, watches, fans, telephones, automobiles, airplanes, radios, cameras, electrical appliances, medical treatments, antibiotics and vaccines, etc., etc. Such technologies strongly influence life and often have unforeseen and unintended consequences. Robots have replaced many humans in the workplace; automobiles and carbon-based power plants are possibly contributing global warming; refrigeration has strongly influenced what we eat and how we distribute our food; processing of corn and soybeans have significantly changed the American diet perhaps resulting in the rising tide of obesity… Even when contributing in a positive way to life, sometimes technology fails as with the collapse of a bridge, the meltdown of a nuclear reactor, the collapse of a building, or with the loss of an airplane due to mechanical problems.

Science, technology, and society strongly interact. Technology has associated with it many problems by virtue of its mere presence within society. Whole areas of life benefit from the availability of technology such as improved transportation, communication, nutrition, sanitation, health care, food production, and agricultural practices. These alone, while quite good, have foreshadowed problems with overpopulation and global pollution. Deforestation, resulting from overpopulation and slash-and-burn agricultural practices, has led to loss of habits, extinction of species, and an increase in CO_2—a greenhouse gas associated with global warming. While antibiotics are themselves good, through overuse and misuse they often have the unintended side effect of encouraging resistant bacterial strains. The use of fossil fuels for energy generation has resulted in pollution of our oceans, soil, and atmosphere, and also contributes to global warming. The use of chlorofluorocarbons as refrigerants has resulted in depletion of the Earth's ozone layer. The threat of nuclear weapons and radiation can result in global annihilation or contamination from dirty bombs. Correcting anticipating the effects of technology can, therefore, be just as important as developing technology itself.

Science has as its primary aim making sense of the physical world. Scientists seek knowledge and understanding; they develop principles, laws, and explanations in the forms of hypotheses and theories. They do not always have as a goal application of that knowledge; rather, they seek knowledge for its own sake. Engineering rarely has explanation and understanding as the primary aim; rather, engineers generally have as a goal the application of scientific laws and principles to solve real-world problems. Science and engineering are both ways of knowing, and exist among other ways of knowing such as history, philosophy, and religion.

The Essence of Science

Science can be characterized as a combination of process and product that helps us understand the nature of the physical world. It is an empirical process that organizes and makes sense of physical experiences. Its product, scientific knowledge, is reasonably durable. Science has a certain epistemological standing due to its reliance upon empirical observation. Citizens place trust in scientists and confidence in scientific findings because science tends to be so successful in solving important problems. This trust in science is justifiable, but not similarly merited by non-science and pseudoscience. Some would argue that history, sociology, and psychology are examples of social science. Others would argue that such things as astrology, creationism, and aromatherapy are examples of pseudoscience. These distinctions are made due to the special status accorded to science. Nonetheless, it should be pointed out that science has many limitations, and that historically it has answered many questions incorrectly.

What makes science *science*? What is it about science that allows it to be distinguished from pseudoscience or non-science? The answer to these questions is by no means clear. It is *not* merely that science is empirical—based only upon what can be observed. Questions that touch upon the unobservable (such as whether or not humans can communicate with the dead or have souls) might seem on the face of it unscientific, but is science any different when scientists speak about hitherto unseen quarks, strings, or dark energy? Still, investigating quarks, strings, and dark energy seems to be the essence of modern physics and astronomy—two of the premiere sciences.

The Problem of Demarcation

What distinguishes genuine science from pseudoscience and non-science? Finding a meaningful answer to this question is known as the problem of demarcation. It has been and remains a central problem in the philosophy of science because it has proven difficult to establish necessary and sufficient conditions that can be used to rule in and rule out specific instances of science so called. This is a problem with important practical and theoretical implications. Pseudosciences claim for themselves that special epistemic status reserved for genuine science, but they do not merit this status. While pseudoscience is often based on observations and sometimes makes correct claims, pseudoscientific and non-scientific claims do not merit the kind of consideration that scientific claims properly deserve. This is not to imply that all pseudoscientific and non-scientific claims are incorrect and that all scientific claims are correct. Even the history of authentic science is filled with false assertions and incorrect conclusions.

Philosopher of science Karl Popper argued that what sets science apart from pseudoscience is its openness to testing and falsifiability (e.g., subject to being shown false), not its inherent empirical basis—observation and experimentation. For instance, astrologers and creationists make appeals to selected observations. But observations are "cheap" according to Popper. Pseudoscientists can find confirmatory evidence just about anywhere they look. Evidence that is selectively gathered and interpreted in light of one's theory is of little value in confirming that theory. Additionally, evidence that contradicts a theory can often be explained away in order to preserve the theory. As a result, Popper argued that fitting data well is not the hallmark of a good scientific theory; it is the theory's ability to predict and explain that gives it scientific worth. In essence, a good theory's predictions should be surprising and, in a certain sense, improbable. Einstein's general theory of relatively became an exemplar of what science is all about because of its ability to account for the subtle changes in the orbit of Mercury, to predict the deflection of starlight as it passed near the sun, and to explain the reddening of starlight as it ascended from high density white dwarf stars. According to Popper, the mark of a genuine scientific theory is its ability to make predictions, provide explanations, and withstand severe testing in the light of observational and experimental evidence. Authentic scientific theories will pass the test of falsifiability because they appear to be consistent with reality. Being subject to the test of falsifiability is a necessary condition for a scientific claim.

While Popper's principle of falsifiability might seem a suitable criterion for distinguishing science from pseudoscience, it has faced severe criticism from philosophers of science. For instance, the claim that "all copper conducts electricity" appears to be a legitimate scientific claim. Still, it does not appear to be falsifiable based on a finite number of observations. Just as important, tests based on probability likely never can be falsified. While rolling a die and turning up a "6" ten times in a row is statistically improbable (with odds of 1 in 60,466,176), it is still possible. Achieving an unexpected result in this case does not necessarily mean that the die is unfair; this combination just happened to turn up. Even when theories fail to account for all possible situations, this does not mean that we must reject them.

While Newton's theory of gravitation could not account for the irregularity in the motion of Mercury’s orbit, it has retained its usefulness. Failure of a conservation law to precisely predict the outcome of, say, a collision, is no reason to reject it due to the complications associated with experimental testing. Medicine is not rejected in light of the fact that it has frequent failings with many patients dying even after receiving the best of medical attention. These examples are not to imply that there is no difference between science and pseudoscience; it’s just that the difference is difficult to characterize, and that better demarcation criteria are needed.

Additional criteria have been proposed to help solve the problem of demarcation. One is that pseudosciences fail to make progress whereas sciences do, indeed, progress. For instance, the explanations and predictions of astrology are no better following the advent of precise measuring instruments and the developments in mathematics, astronomy, and computer technology, than they were centuries ago. On this basis, astrology clearly fails the test. However, on this basis the areas of classical dynamics (large systems at low speed) and thermodynamics also fail the test as legitimate science. Both were “dead” for many years before new areas of physics such as relativity theory and quantum mechanics brought them back to life. That a theory fails to have a clear mechanism also has been used to distinguish science from pseudoscience, but this criterion has a problem as well. While the astrological influence of the planets among the houses and signs has no clear mechanism, some would say that neither does gravitation. To say that a stone released from the hand falls to the ground due to gravity merely provides the pretense of an explanation. Some have suggested that the social practices of science differ from those of pseudosciences. This is, if scientists call something science, it is science—otherwise not. Unfortunately, some institutionalized science (such as

Lysenkoism—a repressive political or social campaign undertaken in the name of science) would be considered science under this criterion. Others have suggested "dubious origins" as a sign of a pseudoscience. Clearly, the authentic sciences of astronomy and chemistry have historical roots in astrology and alchemy, and this criterion does not provide adequate demarcation either. Even the types of reasoning—mathematic or analogical reasoning for instance—do not clearly distinguish science from pseudoscience. Pseudoscientists often depend upon the use of complex formulas and mathematical calculations whereas scientists will sometimes depend upon reasoning by analogy.

Still others have suggested that a good definition of science can be used to distinguish it from pseudoscience or non-science. Anything with a proper pedigree, such as a rigorously applied observational or experimental method, might then be admitted to the exclusive club we call science. But just what are the necessary and sufficient conditions that must be met in order for something to be called a science? (Necessary conditions exclude things that are not science; sufficient conditions include things that are science.)

There are two approaches to characterizing science so as to distinguish it from pseudoscience. One approach is normative and comes from the philosophers of science (e.g., Francis Bacon, John Stuart Mill, Karl Popper, etc.) who say what science *ought to* look like. These philosophers have suggested that science should follow a prescribed set of steps. Whatever incorporates these steps is science. The other approach is historical and comes from philosophers (e.g., Thomas Kuhn) who say what science *actually does* look like. They look at the work of key scientists (exemplars such as Isaac Newton and Albert Einstein) and from such work draw a characterization of science.

If one were to come from the normative perspective of science, one might characterize the method of science as ranging from simple (identify a problem, propose an explanation, use the explanation to make a prediction, test the prediction by experiment or observation, modify the explanation if needed, retest and continue this process recursively) to complex (*Mill's Methods* of agreement, difference, the joint method of agreement and difference, concomitant variations, and residue which are beyond the scope of this book). While these descriptions are useful, they cannot lead from observation to correct causal hypotheses without problem. As history has shown, the fact of the matter is that there is no universal scientific method that can be used to solve all problems.

From a historical perspective, one could argue from the contexts of discovery that there are about as many scientific methods as there are scientists. While some scientists follow the general steps outlined in the traditional scientific method of Bacon, many approaches are also idiosyncratic—particular to the individual. An examination of the history of science shows that many other approaches have been used to conduct the scientific enterprise – from trial and error, to the interpretation of dreams, to serendipitous discovery, to the systematic use of logical, pre-determined procedures.

Trial and error has been, up until the time of the human genome project, the modus operandi for finding new biologically active drugs. This approach historically has been the hallmark of medical research. Conjectures are put forth for experimental testing; what works is retained, what does not work is rejected. Today, drugs can be tailor-made using knowledge of a patient's genetic traits. Other researchers develop physical computational models, such as models of volcanoes, and vary system parameters and relationship to find a model that compares well with reality. Even the interpretation of dreams, as supposedly occurred in the case of Kekulé's articulation of the benzene's cyclical molecular structure, has paid dividends.

Science sometimes proceeds from discovery rather than from exclusively following a logical and systematic method of inquiry. The history of science is littered with serendipitous discoveries—Alexander Fleming's discovery of penicillin, Wilhelm Röntgen's discovery of X rays, Oskar Minkowski's discovery that diabetes stems from a disorder of the pancreas, Charles Richet's discovery of anaphylaxis, Louis Pasteur's discovery of a cholera vaccine, and Jocelyn Bell's discovery of pulsars. These scientists were lucky enough to be in the right place at the right time, and to understand the significance of what they observed. This is not to say that just anyone could have made the discoveries that they did. Each of these scientists worked long and hard to validate their conclusions. What this is intended to say is that sometimes accidents happen that have very interesting consequences if personal knowledge and intellectual engagement play a role in the discovery. As Pasteur said, *"Chance favors the prepared mind."* Knowledge and hard work were the keystones of scientific discovery even in these cases.

From the historical record, it should be clear that it is extremely difficult to accurately characterize science and its ways of knowing. That the problem of demarcation has not been solved can be seen by recent attempts to introduce "scientific" creationism and intelligent design into the public school system. Proponents of these beliefs want them taught on equal footings with established science, and in recent years have made inroads with state boards of education in several of the US states.

Sidebar Story 1—Science and Intelligent Design

Intelligent design is once more appearing in the guise of science. It is an old idea dressed up in new clothing. That this is the case can be seen from a review of the writings of 18th century natural philosophers and theologians. Over the past year the author has been reviewing the writings of renowned philosophers from this time period. Among the most interesting writers of this era from a scientific perspective is English philosopher David Hume (1711-1776). Late in life, Hume wrote *Dialogues Concerning Natural Religion*. The work was published posthumously in 1779. Reading this work today will make one feel that it was written only recently, and in direct response to the claims of intelligent design proponents. Consider some of the following ideas that stem from this monumental work:

- In order for a claim to be scientific, it must be subject to and comply with the rules of scientific evidence; for a claim to be credible, it must be supported by evidence that satisfies scientific skeptics; scientific skepticism must be free from prejudice; the more amazing a claim, the greater the required evidence.

- God is defined by intelligent designers as that which created the universe; this definition does not provide knowledge with certainty, merely unsubstantiated belief; a definition does not imply knowledge; there are no incontrovertible proofs of God's existence; if we assume a god as creator, we are less concerned about a belief in that god and more concerned about his nature.

- Religious belief based on authority is not as certain as scientific knowledge based on empirical observation; for instance, it is reasonable to infer from experience that houses and watches have house builders and watchmakers; no similar claim can be made for the universe because we cannot make a general inference based on a single observation; a god's creation of the universe is merely conjectural.

- Order in the universe does not necessitate intelligent design; there are examples of order which are quite natural; for instance, consider crystals and density columns; inferences must be based on experience and are specific to experience; while ships have builders, it is not reasonable to assume that the universe does;

arguing from analogy—a posteriori —is at best weak, and a poor substitute for direct evidence of the existence of a god.

- The study of a leaf can not lead to necessarily correct implications for the origin of a tree; only a preponderance of a wide variety of evidence can lead to reasonable implications; unlike the creation of a house, a watch, or a ship, the creation of the universe is not self-evident and undeniable; we must be careful to distinguish reasoning from experience, but especially when it relates to matters of fact; we do not have enough experience with the creations of universes to draw sound conclusions.

- Explaining the order of the universe by referring to a god explains nothing; we merely replace ignorance about the origin of the universe by something which is itself conjectural; we are obliged then to find out more about the cause of this cause which is impossible to satisfy; objective scientists avoid the demand for closure and leave unanswerable questions unanswered until such time as evidence itself forces a conclusion; admitting ignorance is better than drawing unsubstantiated conclusions about a god whose existence is merely conjectural.

- By studying a universe supposedly designed by a god, we can conclude something about the attributes of the designer; the universe does not appear to be free from “every error, mistake, or incoherence” in the designer’s undertaking; consider pain, sickness, and death, and their relation to modern medical sciences; consider hunger and starvation, and their relation to the green revolution; humans are constantly improving upon creation; can we infer thereby that the deity was inexperienced, negligent, cruel, shortsighted, and inferior - with a deficit of perfections?

- With the apparent conflicts between good and evil in our world, the tug and pull of countervailing forces in the universe, we can not preclude the idea that the designer might have been two instead of one; the designers/creators of the universe might be good/evil or male/female, each contributing traits to creation; intelligent design weakens the proof for the very existence of the one God that intelligent design proponents seek to show exists.

Given these few points—only some of the many more made by Hume over 200 years ago— those who promote intelligent design should be careful of the consequences on religious beliefs that promoting this concept as “science” might have. To promote intelligent design as science is to open religious belief to the critique of rational empiricism. All science teachers—as well a promoters of intelligent design—would benefit from a careful reading of Hume’s *Dialogues Concerning Natural Religion*.

Sidebar story #1 shows why it is important understand the nature of science and how it differs from other ways of knowing. There are other profound implications associated with the failure to clearly distinguish science from pseudoscience. Which theories should be eligible for research funding? Which procedures should be admitted to medical practice? Which activities or materials should be banned as a risk to public health and well-being? A good definition of science that might rule in certain belief systems and rule out others does not exist. The fact that acceptable demarcation criteria have yet to be established does not mean that such criteria cannot be formulated. The philosophers of science still have their work cut out for them.

Scientists, on the other hand, will often take a more pragmatic view of science, and provide a characterization that allows science to be distinguished from science so-called. Science is based upon repeatable and verifiable observations that are open to all observers. An observation must be repeatable and verifiable by any observer (within experimental uncertainty) who cares to repeat and check another's observation if it is to count as evidence. Anecdotal evidence—onetime observations made by individual observers—have little value as evidence in the broader scientific community; there is no such thing in science as a "preferred observer." Neither does science make selective use of evidence. A case that demonstrates the failure of a "scientific claim" to fail the tests of repeatability and verifiability was the 1989 public announcement by physicists Pons and Fleischman that they had achieved "cold fusion" in the laboratory. They claimed to have replicated the nuclear fusion processes taking place at the core of the Sun in a jar of water at room temperature without destructive side effects. A skeptical scientific community rushed forward to evaluate their claim. Within a few months it was clear that reality did not compare favorably with the claims, and the work was entirely discredited. As this example shows, science is open to change and self-correcting in the light of new evidence. Science is not based upon authority (famous scientists, religious leaders, sacred texts, etc.); scientists are only human and they often can and do make mistakes.

Teaching the Nature of Science

To help students understand the nature of science, good science teachers will infuse considerations for the nature of science throughout their instruction. While teaching about the nature of science might be limited in scope and duration on any one day, it is generally ongoing, explicit, and in context. Poor science teaching assumes that students will learn about the nature of science implicitly through lecture, problem solving, and cookbook lab experiences. While this assumption is true to a limited extent, using an inquiry approach and teaching directly about the nature of science on a regular basis and in context will likely be considerably more effective. To successfully teach about the nature of science, teachers must possess essential understandings, suitable pedagogical practices, and appropriate motivation so they can maximize what their students learn in this important topic area.

If college students have taken several years of didactic science content courses (and rarely a philosophy or history of science course), it is understandable why they have such a limited knowledge of the nature of science. Given the traditional textbook approach of teaching by telling, how can we expect science teacher candidates to impart a suitable understanding of the nature of science to their own students? Logically speaking, we cannot. Teachers cannot effectively teach what they do not know and understand. While there have been volumes written about the nature of science and its relationship to science literacy, very little information has been provided about how to actually teach students so that they can develop the expected understanding of the nature of science. It would be presumptuous of any author to think that he could fully describe and explain everything a teacher candidate should know about the nature of science in a single textbook chapter. Only a book-length manuscript would be sufficient for this purpose. Nonetheless, it is imperative to have a suitable working definition of what is meant by the nature of science if progress toward that goal is to be made and assessed.

To What Does “Nature of Science” Refer?

As noted earlier, the concept of “nature of science” is complex and multifaceted. It involves aspects of philosophy, sociology, and the history of science (Curd & Cover, 1998; McComas, Clough, & Almazroa, 1998). It is surrounded by numerous issues (Alters, 1997; Labinger & Collins, 2001; Laudan, 1990), and is rather complex as the review of any relatively recent philosophy of science book will show (e.g., Bakker & Clark, 1988; Klee, 1997).

Authors variously define what constitutes the nature of science (NOS), and what students should know to be “NOS literate.” For instance, Aldridge et al. (1997) see the processes of scientific inquiry and the certainty of scientific knowledge as being central to understanding NOS. Lederman (1992, p. 498) states, “Typically, NOS refers to the epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development.” Lederman et al. (2002) define NOS in part by referring to understandings about the nature of scientific knowledge. These understandings deal with science’s empirical nature, its creative and imaginative nature, its theory-laden nature, its social and cultural embeddedness, and its tentative nature. They also express concern about understandings relating to “the myth of The Scientific Method.” Project 2061’s *Science for All Americans* (AAAS, 1989) and *Benchmarks for Science Literacy* (AAAS, 1993) both regard understandings about scientific worldview, scientific inquiry, and the scientific enterprise as being central to a comprehensive understanding of the nature of science. According to the Project 2061 authors, a scientific worldview consists of beliefs that the world is understandable, that scientific ideas are subject to change, that scientific ideas are durable, and that science cannot provide complete answers to all questions.

In addition, individuals will understand the processes of inquiry and know that science demands evidence, is a blend of logic and imagination, and explains and predicts, but is not authoritarian. Those who are NOS literate will also be knowledgeable about the scientific enterprise. They will understand that science is a complex social activity, that science is organized into content disciplines and is conducted at various institutions, that there are generally accepted ethical principles in the conduct of science, and that scientists participate in public affairs both as specialists and as citizens. They attempt to avoid bias.

The National Research Council in *National Science Education Standards* (NRC, 1996) sees scientific inquiry, the human aspects of science, and the role that science has played in the development of various cultures as being central to understanding the nature of science.

These characterizations of what constitutes the nature of science are incomplete. Many more things could be added to these characterizations such as an understanding that science is self-correcting, that scientists assume a naturalistic world view, that science most often advances as a result of incremental change which is just as important as if not more important than genius, and that the primary roles of science consist of explanation and prediction.

To achieve the goal of having students become broadly NOS literate, we must first identify essential understandings about NOS, and provide an implementation model, practical advice, and motivation for implementing appropriate NOS literacy practices in the classroom.

Essential Understandings about NOS

Statements about what it means to be NOS literate are inadequate for planning purposes to the extent that they do not provide a detailed definition. Successfully teaching NOS necessarily will be predicated on a nominal definition of what it means to be NOS literate. Individuals with a broad understanding of the nature of science will possess knowledge of the content and history of at least one science discipline, plus knowledge of associated scientific nomenclature, intellectual process skills, rules of scientific evidence, postulates of science, scientific dispositions, major misconceptions about NOS, an understanding of the unifying concepts and processes of science, and an understanding of the limitations of science.

While this definition appears rather comprehensive, it takes an admittedly simple if not simplistic view of NOS. Nonetheless, judgment about what constitutes an adequate understanding of the nature of science must be based on the practicalities of teacher preparation. While it would be ideal if every teacher candidate would take courses dealing with the philosophy and the history of science, it too infrequently happens due to the lack of such courses or as a result of the prodigious number of graduation requirements placed on science education majors. As a consequence, we use a pragmatic operational definition tempered by the requirement that we must be able to address the various components of the definition in our physical science content and teaching methods courses. It should be noted that a reasonably comprehensive understanding of science content knowledge is not addressed, but is assumed.

Scientific Nomenclature

A common language is essential to accurately communicate ideas (Hirsch, 1987), and this is true in relation to NOS. As such, the author has identified 24 terms that are most closely associated with both the experimental and epistemological concepts relating to NOS. These terms represent the minimal vocabulary and concepts with which every teacher candidate, teacher, and their students should be familiar. The terms, along with their definitions, appear in Table C-1.

Table C-1

Essential Scientific Nomenclature with Definitions: Twenty-Four Fundamental Terms and Concepts with which Science Teachers and Their Students Should be Familiar

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- **Assumption**—a statement, thought or idea held with reasonable certainty, but for which there is no proof.
- **Belief**—a firmly held conviction thought to be consistent with reality, but for which empirical evidence does not exist.
- **Control**—a comparison group or situation.
- **Data**—Data (plural, datum singular) are symbolic representations of events or states. Data are generally recorded as discrete bits of raw information. They are not interpretations of evidence; rather, they constitute the evidence itself. Data can be analyzed to produce facts or generate hypotheses.
- **Deduction**—the process of making a prediction on the basis of a hypothesis or theory.
- **Empirical**—verified by observational or experimental evidence.
- **Evidence**—a collection of information or facts that lead to the belief that a conclusion is proper and valid.
- **Explanation**—a series of statements or an account that makes a situation understandable.
- **Fact**—an interpretive statement or conclusion based on evidence. A fact is something that any rational, well-informed group of observers would agree upon. An example of a fact is, “My car’s engine contains four and a half quarts of oil.” A simple measurement will show this to be the case, and no one in his or her right mind would disagree in any meaningful way.
- **Hypothesis**—a tentative explanation of a situation that can be tested thoroughly and that is intended to direct further investigation of the situation or discussion of the facts in the situation. An example of a hypothesis might be that a flashlight fails to work because its batteries are dead. To see if the hypothesis is correct, one might replace the supposedly bad batteries with fresh batteries. If that does not work, a new hypothesis is generated such as has to do with the possibility of a burned out light bulb.
- **Induction**—the process of reasoning from specific cases to a general rule.

(table continues)

- **Knowledge**—a belief substantiated with empirical evidence.

- **Law**—a time-tested, precise statement of a relation between particular variables or a sequence of events that always occurs under particular conditions. Newton's second law of motion (F = ma) is an example of a law because it states a precise relation between three variables (mass, acceleration, and net force) that always occurs under particular conditions (i.e. as long as those variables are describing the same object.)

- **Model**—a tentative mental construct or physical object with explanatory power that corresponds to another real-world object or event; models might also take the form of equations or simulation; they are not as detailed as theories.

- **Paradigm**—a world view, model, or a way of looking at situations that make them understandable.

- **Parameter**—the value of a variable that helps define a situation; the value of a controlled variable.

- **Postulate**—See assumption.

- **Prediction**—A prediction is a statement of what will happen in the future. An example of a prediction is, "When I increase the amount of pressure on the object, it will shrink in size."

- **Principle—**A principle is a general rule or statement of a relationship seen in nature, in the operation of a machine, or in a system. For example, Bernoulli's principle states that fluid in a moving stream has lower pressure than the surrounding fluid. When an object gets hotter it becomes brighter and bluer. Friction tends to oppose motion. Total energy is conserved. Momentum is conserved.

- **Proof**—confirmation of a conclusion using logical statements or other evidence.

- **Pseudoscience**—a "false science;" something that purports to be science but is not.

- **System**—a single entity, or one or more interacting entities, that can be studied in isolation from its surroundings.

- **Theory**—A theory is an extremely well substantiated hypothesis. It is a precise statement that applies to a wide range of situations, and that has a track record of satisfactorily accounting for the known facts in those situations. It has a great predictive and explanatory power. An example of a theory is the special theory of relativity.

- **Variable**—one or more elements, features, or factors of a system that can be manipulated.

Intellectual Process Skills

Students cannot have a comprehensive understanding of the nature of science if they do not have first-hand experiences with the empirical methods of science. Table C-2 gives a list of essential process skills that will be learned when science is taught using inquiry-oriented teaching methods.

Table C-2

Some of the Many Intellectual Process Skills to be Addressed in Introductory Laboratory Activities

- Generating principles through induction
- Explaining and predicting
- Observing and recording data
- Identifying and controlling variables
- Constructing a graph to find relationships
- Designing and conducting scientific investigations
- Using technology and math during investigations
- Drawing conclusions from evidence

Rules of Scientific Evidence

The rules of scientific evidence have been a topic of considerable attention for notable scientists and philosophers ever since the "Enlightenment" of the 17th century (e.g., Pascal, Leibniz, Galileo, Newton, Bacon, Berkeley, Hume, Hobbes, Locke, and Kant to name but a few). Nonetheless, to the best of the author's knowledge, the rules of scientific evidence have never been codified in an easily accessible way. There is a need for such if treatment of this subject matter is ever to be addressed systematically through teaching. What follows is a simple compilation of such. There is no claim of completeness, and no claim that every scientist or philosopher of science would agree with all these statements. Readers are cautioned that characterizations are, at best, tentative. No form of hierarchy is to be inferred on the basis of order. This list is a point of departure for those who would like to talk about rules of scientific evidence with students.

- For a claim to be scientific it must be testable; by this characterization a claim need not be accurate to be scientific.
- The ultimate authority in science is empirical evidence based on observation or experimentation.
- Scientific conclusions must be based on public evidence; it is improper to make or accept any claim without sufficient supporting evidence.
- Correlation should not be confused with cause and effect; scientists do not accept coincidence or unlinked or unsupportable correlations as proofs.
- Scientific claims, to be acceptable, must not conflict with what is known with relative certainty; nonetheless, it should be kept in mind that scientific creativity sometimes contradicts conventional understanding.
- Scientists should be skeptical of claims that conflict with accepted views of reality; they should avoid bias and be particularly objective in their treatment of claims of which they are skeptical.
- Scientists should test and independently verify all significant and apparently justifiable claims, especially those that appear to contradict conventional thinking and/or prior evidence.
- The more unconventional a claim, the greater the requirement for supporting evidence; anecdotal evidence is insufficient proof of any scientific claim.
- Scientists must not make selective use of evidence; they must not promote a

particular belief by suppressing evidence or fail to seek contradictory evidence by avoiding investigation.

- Only one positive instance is required to refute a negative claim.
- Multiple positive instances alone cannot prove a positive claim unless all cases are examined.

- One should not assume as certain that which one is attempting to demonstrate; this can lead to false conclusions.

- If several explanations account for the same phenomenon, the more elegant explanation is preferred (parsimony or Ockham's razor); a single comprehensive proposition is to be valued over a number of ad hoc propositions.

- Theoretical constructs can be valued over empirical evidence or developments under certain conditions.

Postulates of Science

Postulates of science are the assumptions upon which science operates. They serve as the basis for scientific work and thought, and to some extent determine what is admissible or inadmissible under the rules of scientific evidence. To the best of the author's knowledge, postulates of science are often referred to, but as the rules of scientific evidence, they do not appear to have been codified. Nonetheless, for the sake of educating science-teaching majors about NOS, we have adopted the following statements as representative of the postulates of science. Again, as with the rules of scientific evidence, there is no guarantee that this list is comprehensive or that all scientists or philosophers of science would agree with these postulates and their characterizations. Indeed, in the light of quantum physics some philosophers of science have argued that several of the postulates are mutually exclusive. We have adopted a pragmatic view for the sake of teacher candidates studying and teaching classical physics during their student teaching practicum.

- Nature is the same universally; all laws of science are universal and not merely local. The universe is, therefore, understandable and predictable.
- The properties of a material are likewise universal; the properties of a sample can be generalized to all such material.
- There is a consistency in the way that nature operates in both time and space; the natural processes in operation today can explain physical events—past, present, and future.
- No observed effect exists without a natural cause, but sequence—no matter how frequently repeated—does not necessarily infer cause and effect.
- Scientists do not accept any kind of explanation for which no test is available; while objective scientists will preclude theological explanations, this must not be taken to imply that they are necessarily atheistic.
- Science admits, in addition to observable, repeatable observations, natural entities that might not be directly observed but whose existence can be theoretically inferred through reason.
- Scientific knowledge is durable but tentative, and is subject to revision; science does not provide us with absolute certainty.
- While science does not provide for absolute certainty, proofs beyond a reasonable doubt are possible.
- Science is not a private matter that concerns the individual scientist alone; rather, science is a social compact, and scientific knowledge represents the consensus opinion of the scientific community.

Scientific Dispositions

Science for All Americans (AAAS, 1989) identifies several general characterizations that describe suitable dispositions for scientists. *Benchmarks for Science Literacy* (AAAS, 1993) similarly addresses desirable “habits of mind”—the values and attitudes—looked for in scientists. The major points of these two works have been encapsulated in the following listing.

Desirable characteristics of scientists are:

- curious and skeptical—they are on the lookout to discover new things and demand suitable evidence for claims; they avoid unwarranted closure.

- objective and not dogmatic—they demonstrate intellectual integrity and avoid personal bias; they are open to revision in the face of incontrovertible evidence.
- creative and logical—they attempt to provide rational explanations on the basis of what is already accepted as established fact.
- intellectually honest and trustworthy—they realize that science is a social compact, and abide by the ethical principles of the science community.

Major Misconceptions about Science

McComas (1996) has identified what he feels are the major misconceptions—false beliefs—that many non-scientists (and even some scientists) hold to be true about science.

- *There exists a traditional scientific method that is general and universal*. Students are sometimes led to believe that the scientific method can be used to solve all problems. The method, based on a 1620 work by Francis Bacon, goes something like this: (a) identify a problem, (b) gather information, (c) formulate a hypothesis, (d) test the hypothesis, and (e) draw conclusions. While this approach does sometimes work (such as in the repair of a flashlight), other methods of scientific investigation can and do work when the traditional scientific method does not.

- *Misconception: Hypotheses are really only educated guesses*. Hypotheses are tentative explanations that account for or relates a set of known circumstances. They have limited explanatory power and can be used to generate predictions that can be put to experimental or observational tests. Hypotheses should never be confused with predictions. Predictions are forecasts of what will happen, but not why they will happen.

- *Misconception: Hypotheses turn into theories that eventually become enshrined as laws*. Laws express the relationships that exist between two or more variables. As such, they have no explanatory power. Hypotheses, like theories, do have explanatory power. Hypotheses can the thought of as provisional, tentative, or immature explanations that account for a limited number of observations. Theories are much more comprehensive than hypotheses and have great explanatory and predictive power.

- *Misconception: Scientific knowledge is based mainly on experiment*. Science is supported by experiment, observation, and hypothesis and theory development.

While physicists might conduct controlled experiments in the main, much of the work in other areas of science such as astronomy, biology, and zoology are based on observation. Hypothesis and theory development typically result from detailed and careful introspection.

- *Misconception: High objectivity is the hallmark of science*. Scientists are human and, as such, are subject to the same foibles and failings as other humans. Scientists have beliefs, preconceptions, misunderstandings, biases, and paradigms that influence the way they can and do view the world. The scientific community has not infrequently ruled out beliefs that were later shown to be correct such as germ theory, continental drift, and warm-blooded dinosaurs.

- *Misconception: Scientists always review and check the work of their colleagues*. While this is sometimes the case with unexpected claims (such as with cold fusion), it is not always the case. Much of what is purported to be science is never reviewed in depth by peers concerned with their own projects and working with limited resources. Fortunately, peer review in professional journals helps to catch the most egregious errors.

- *Misconception: Certainty results when facts are accumulated and analyzed*. Scientist often use inductive processes to formulate principles, laws, and other sorts of conclusions. The problem with induction is that these general rules are generated on the basis of limited observations. There is no guarantee that these general rules will apply in all cases.

- *Misconception: Science is less creative than it is procedural*. Much of the success of scientists is based on factors other than mere process. Flashes of insight, prior knowledge, chance discoveries, accidents, and serendipity all play a role in the scientific process. As noted above, there is no systematic, uniform method of science.

- *Misconception: The scientific method leads to absolute certainty*. While science has a track record of developing “good” scientific conclusions, there is certainly no claim that science and the work of scientists will forever be without error or fault. In science, the only things known to be “true” are those things that have been shown to be false – as only one case is necessary. It is impossible to “prove” something infallibly true because any single observation in the future might show the conclusion to be in error. Science knowledge is, at best, durable; scientific claims will forever be tentative.

- *Misconception: All questions posed by the universe can be answered by science*. There are many areas in which science can play no role. Because science is based on empirical evidence, only evidence-based claims can be made or examined. Anything that is not falsifiable falls outside the realm of science. Science cannot tell us how many angels can dance on the head of a pin, or whether angels even exist.

Unifying Concepts and Processes of Science

Any understanding about the nature of science would be incomplete were it not to include an understanding of the unifying concepts and processes of science. Students often are left with the false impression that chemistry is completely separated from physics which is separated from earth and space science which is separated from the biological sciences and so on. The reality is that boundaries between each of these disciplines are vague and constantly changing. Common concepts and processes bind the disciplines together; they are fundamental to each science and comprehensive in their coverage. Students must come to understand that the basic approaches in one discipline are shared with another. Skills used in the study of one discipline can readily be transferred to another. The NSES gives the unifying elements as shown in Table C-3. Students need to understand these if they are to have a comprehensive understanding of the nature of science.

Table C-3

Unifying Concepts and Processes of Science

- Systems, order, and organization
- Evidence, models, and explanation
- Constancy, change, and measurement
- Evolution and equilibrium
- Form and function

Science is focused on understanding the world in all its complexity. The study of phenomena is often broken down into smaller areas of study as a matter of convenience and to allow specialization; hence, the development of the various science disciplines. Selected interacting components of the world constitute systems, and it is these systems —some complex and others simple—that scientists study. A system might consist of a single cell, or the interaction of water with the land, ocean, and atmosphere, or of independent and dependent variables in an electrical circuit. Scientists study these systems in an effort to find organization patterns or regularities that are referred to as order. Newton's laws, Kepler's laws, the Krebs cycle, Darwin's law of natural selection, and the conservation laws of matter, energy, momentum, and charge are all examples of order. The study of systems also allows for the recognition of organizational patterns within nature. Systems are anything that can be ideally isolated as regions of attention. Examples of system might be a cart rolling down an inclined plane, a body falling free from wind resistance, a series of interacting bodies and fields, or a thermodynamic system. Scientists recognize patterns such as the periodic table of elements, and the classification of organisms into kingdoms, phyla, class, order, and species. There are organizational patterns even within living things as well such as cells, tissues, organs, and systems. The sciences are unified to the extent that they all study systems, the purpose of which is to find order.

By its very nature science, in all its disciplines, is empirical; that is, its conclusions depend upon reasoned use of evidence. Logical use of evidence often allows for the development of principles, laws, models and hypotheses, and provides for the generation of predictions. Science is more than merely descriptive. An analysis of systems can also sometimes lead to explanation. The purpose of science is not merely to state, "The sky is blue." Rather, it is to explain if possible why the sky is blue. Science does not deal with teleological matters (argument from design or purpose), but it will identify the physical phenomenon responsible for this blueness if possible (Rayleigh scattering). Scientists do not have sustainable explanations for all the fundamental forces of nature—they just "are."

Measurement in science is fundamental. Evidence, derived from observations and experiments, is the basis from which constancy and change are determined. From the study of nature and its interacting parts, scientists have been able to identify a form of constancy known as conservation. There is conservation of charge, mass, energy, momentum, symmetry, and parity. Each of these is central to making predictions and providing explanations. Changes in systems allow for the creation of principles or laws that describe the relationship between an independent and one or more dependent variables. Scale (using different systems of measurement) and rate (the time-based change of a variable) are central to understanding the concept of measurement. Closely related to measurement is the concept of equilibrium. This is a physical state in which two or more values or rates operate in various magnitudes or directions to offset one another. Balance, steady state, and homeostasis are all terms descriptive of equilibrium.

Evolution, as well as form and function, are most closely associated with biological systems. Nonetheless, evolution of the universe, and other remarkable changes over time such as the "evolution" of galaxies, stars and planets, is worthy subject matter for physical science students. So too is the "evolution" of knowledge within the scientific enterprise.

Systems, models, constancy and change, and scale are suitable subject matter for science instruction.

The Limitations of Science

By its nature as an empirical study of the world, science is limited. That is, science cannot provide complete answers to all questions. Issues involving morals, value judgments, and social concerns can be enlightened by the information that science provides, but science cannot be asked to make decisions in these non-science areas—only used. Answering such questions as, “Do humans have souls?” and “Given what we know, should we act now in an attempt to reverse global warming?” and “Is war ever morally defensible?” and “How can we solve this or that social ill?” is beyond the scope of science. Science is only one way of knowing about the physical world. Other means of knowing include religion, ethics, politics, philosophy, history, psychology, and so on. These ways of knowing also must contribute to finding answers to questions that science alone is unable to answer.

Science, as a very human endeavor to understand the physical world, is also subject to error and revision. Science—like scientists—is fallible, but it is also self-correcting. Early on it was believed that the Sun orbited the Earth. Only after the development of technological instruments such as the telescope, and increased understanding of the laws of motion, were scientists able to rectify this error. Heat was once thought to originate with phlogiston and caloric; it is today realized to be just another of the many manifestations of energy.

Students have to understand that there are questions that science cannot answer and problems that it cannot solve. Many of humanity’s questions do not revolve around the physical world; rather, they relate to many non-scientific matters. Many of the world's problems stem from intentional human action, and there is little that science can do to control these actions. Science is not a "one-size-fits-all solution" to the world's problems. It is only one of many tools in society's toolbox that can be used to answer questions.

The Role of History in Understanding the Nature of Science

History plays a critical role in the development of student understanding of the nature of science. Understanding the historical context of a scientific model, for instance, can help students comprehend the scientific process and role of cultures in its development. Historical treatments of the nature of the solar system (addressing basic astronomical motions and the explanatory work of Ptolemy, Copernicus, Kepler, and Galileo), of gravitation (Kepler's laws of planetary motion, the explanation of by Newton using the law of gravity, and the prediction of the return of a bright comet by Halley), of relativity (Galilean frames of reference, Lorentz's transforms, Einstein's special and general theories), the age of Earth (Lyell's principles of geology, Darwinian evolution), of the shaping of the Earth's features (the jigsaw pattern of the continents, Wegener's hypothesis of continental drift, evidence for and explanatory power of plate tectonics), of the nature of fire (Lavoisier's work relating to conservation of matter, Dalton's quantification of reactions), of splitting the atom (work of the Curies, Rutherford, Meitner, Einstein, and Fermi), and of harnessing power (industrial revolution), can all provide the underpinnings for understanding the nature of science. Providing historical vignettes such as found in sidebar stories #2 and #3 can improve student understanding of the nature of science.

Sidebar Story 2—Newton's Formulation of the

Theory of Gravitation (The Simple Case)

There are several geniuses in the field of Renaissance astronomy and physics known to almost every educated person—Copernicus, Galileo, Kepler, and Newton among them. What was the creative genius of these individuals? While it would take an encyclopedic book to be able to answer that question, the current paper is much more modest. It is the purpose of this paper to explain in very few words the creative genius of Isaac Newton in relation to his formulation of the theory of gravitation. (It is called here a theory rather than a law because of the empirical evidence that has been built up over the years in verification of the hypothetical form of the mathematical formulation that was not derived from experiment—e.g., a law.)

The story of Newton sitting under an apple tree one day seeing an apple fall and thinking about the form of gravitation is probably apocryphal. Nonetheless, it could have occurred to Newton that the fall of an apple is not unlike that of the fall of the Moon as it orbits the Earth. It was the fact that he was able to understanding the relationship between the Moon and the apple that constitutes the real creative genius of Isaac Newton. Couched in modern metric terms, this is what Newton did....

He realized that the acceleration of, say, an apple near the surface of the Earth was 9.8 m/s^2 (in modern terms). That is,

$$a_{\oplus} = 9.8 \frac{m}{s^2}$$

He then calculated the centripetal acceleration of the Moon in its orbit around the Earth by using an equation first provided by the Dutch scientists of his day:

$$a_{\rightmoon} = \frac{v^2}{r}$$

The speed of the Moon's motion was easily derived from the relationship into which he put the proper values for the orbital radius of the Moon and its sidereal period (both known with a high degree of precision in his day)

$$v = \frac{d}{t} = \frac{circumference}{period} = \frac{2\pi r}{P} = \frac{2\pi(384{,}000{,}000m)}{2{,}360{,}000s} = 1020m/s$$

Using the equation for centripetal acceleration, he then came up with the value of the Moon's acceleration

$$a_{\supset} = \frac{(1020m/s)^2}{384{,}000{,}000m} = 0.00271m/s^2$$

He then compared the acceleration of objects near the Earth's surface with that of the Moon in orbit and found

$$\frac{a_{\oplus}}{a_{\supset}} = \frac{9.8m/s^2}{0.00271m/s^2} = 3600 = 60^2$$

In this case, 60 represented the radius of the Moon's orbit in Earth radii. From this comparison, Newton was able to conclude that the acceleration of the Moon in its orbit was inversely proportional to its distance from the center of the Earth squared. That is,

$$a_{\supset} \propto \frac{1}{r_{\supset}^2}$$

Given the fact that *F=ma,* Newton concluded that the force required to hold the Moon in its orbit around the Earth (and any planet in orbit around the Sun) was similarly dependent upon distance squared. That is,

$$F \propto \frac{1}{r^2}$$

Because gravity is responsible for the perceived weight of objects, and is proportional to the mass of the object, m, (and supposedly the mass of the gravitating body, M), Newton was able to hypothesize that,

$$F \propto \frac{Mm}{r^2}$$

Inserting the proportionality constant, G, gives us the familiar form of Newton's formulation.

$$F = \frac{GMm}{r^2}$$

So, it should be evident from this deduction that Newton's act of creative genius was in the fact that he was able to use observational evidence to formulate a hypothetical relationship for the nature of the central gravitational force required to keep objects in orbital motion. Now, how could this hypothesis be tested? A generation earlier, Johannes Kepler formulated three planetary laws of motion based upon observation of the planet Mars. He stated these laws thusly:

1. Planets move in elliptical orbits around the Sun with the Sun located at one of the foci.
2. The radius arm between a planet and the Sun sweeps out equal areas in equal time intervals.
3. The period of a planet expressed in years squared equals the semi-major axis (mean radius) of the orbit expressed in astronomical units cubed. That is,

$$P^2 = r^3$$

If the units are arbitrary (e.g., SI units), then the form of the equation would be

$$P^2 = kr^3$$

where the value and units of k would depend upon the units employed in the equation's other variables. At this point Newton, with his new formulation of gravity and his own second law, was able to write

$$F = ma = \frac{mv^2}{r} = \frac{GMm}{r^2}$$

Substituting for v $(2\pi r/P)$ and canceling, Newton arrived at the following relationship using the two rightmost components of this equation. That is,

$$P^2 = \frac{4\pi^2 r^3}{GM} = kr^3$$

which is Kepler's third or harmonic law! Newton's formulation of the law of gravity therefore was able to explain why the harmonic law was of the nature derived by Kepler – it's because gravity has an inverse-squared nature. Newton was also able to use his hypothetical formulation of gravity to explain for the ocean tides, account for the shape of the Earth, and give a reason for the speeds of the planets in various parts of their orbits. Hypothesis then, with this firm underpinning, was on its way to becoming theory.

Note that this formulation is for the simple case that assumes purely circular motion. In reality, the solar system's moons and planets move with elliptical and barycentric motion. Taking both of these considerations into account, Newton was able to derive a more precise form of the Harmonic law

$$(M + m)P^2 = \frac{4\pi^2 r^3}{G}$$

where M and m are the masses of the bodies in, say, SI units. If M and m are expressed in solar mass units, P in years, and r in astronomical units, then the equation simplifies to

$$(M + m)P^2 = r^3$$

This relationship was used to measure the masses of various solar system bodies in solar mass units centuries before the space age. Fly-bys of moons and planets with interplanetary spacecraft have verified this relationship, and provide additional evidence that Newton's formulation of gravity is correct. Additionally, sending spacecraft on interplanetary missions using Newton's formulation of gravity as a guide has proven to be extremely accurate, showing once again that Newton was correct in his hypothetical assertion of the nature of gravity. The hypothetical form of the law of gravitation has become well-substantiated theory due to the vast amount of empirical evidence that supports it.

It should be noted, too, that Newton's more detailed analysis of the central force problem resulted in a prediction of elliptical motion—precisely what Kepler had observed. Kepler's law of equal areas is also readily explained by Newton's formulation of gravity. These derivations are beyond the scope of this book.

Sidebar Story 3—An Empirical Basis for Kinetic Energy

Physics teachers sometimes introduce the study of kinetic energy by stating without explanation or justification that kinetic energy is equal to one half the product of the mass and squared velocity. If a basis for this formulation is given at all, it often leaves students confused. Any reasonably skeptical student of physics would want to inquire as to the physical reason why kinetic energy is so defined. The simplest answer is that work and kinetic energy so defined are conserved in certain situations. Is there a laboratory activity that physics teachers might employ to help introductory physics students understand that kinetic energy is indeed proportional to mass and squared velocity and that this in turn is related to kinetic energy? Fortunately, the answer is yes.

What follows is the outline of an introductory physics laboratory that follows a historical approached described by Thomas Young in an 1801 presentation delivered to the Royal Institution in London. By dropping metallic balls of varying mass (diameter appears to be irrelevant) from a constant height and counting the number of droplets of water required to fill a pit created in a clay target, it is possible to show that the work required to produce each depression is directly proportional to the mass of the falling ball. (See Figure 1.) By dropping a ball of known mass from different heights (again, the diameter appears to be irrelevant), it is possible to show that the kinetic energy contained in each release of the ball is proportional to the speed at impact squared. (See Figure 2.) From this evidence it is possible to conclude that

$$KE_{impact} \propto mv^2$$

Deriving the constant of proportionality algebraically can be done by referring to the kinematic formula employed to calculate the speed of impact.

$$v^2 - v_o^2 = 2gh$$

From this is derived the equation for speed at impact

$$v = \sqrt{2gh}$$

Squaring both sides of this latter equation and multiplying by *m* results in

$$mv^2 = 2mgh$$

At this point, it is possible to realize that the work required to raise each ball of mass m to the release height h above the clay in a gravitational field g ($PE_{release} = mgh$) can be separated from the factor of 2, yielding the now familiar relationship

$$\frac{1}{2}mv^2 = mgh$$

or by definition

$$KE_{impact} = PE_{release}$$

It is important to note that this process points to the principle of conservation of energy and might serve as the first encounter with the concept for many students. Perhaps just as important is the conclusion that certain kinematics laws take the form they do because of conservation of energy.

This experiment has been conducted successfully with college students, and 5th through 8th grade school children and their parents. They have used metal spheres with diameters ranging from $2cm$ to $5cm$, and with masses varying from $30g$ to $470g$. Release heights for these balls range from about $50cm$ to as much as $2m$. Larger masses and release heights are to be preferred to minimize the relative error in volume measurement. Once the deformation appears in the clay target, younger students can use water and an eyedropper to measure the volume of the pit. They count the number of droplets of water required to fill the depression completely. Soap is added to the water to reduce surface tension and alleviate any problems with a meniscus. Multiple independent measurements of the volume are important for minimizing error using the water drop method.

An alternative approach for determining the volume of the depression is to use measurements along with the following mathematical formula:

$$V = \frac{\pi x}{6}\left(3r^2 + x^2\right)$$

where the depth of the pit at its center is x, and the radius of the pit is r. The value of r can be determined readily from the semi-diameter of the pit. The value of x is hard to measure directly with ordinary lab instruments, but its value can be found indirectly from the following relationship:

$$x = R - \sqrt{R^2 - r^2}$$

where R equals the radius of the metal sphere.

The clay "target" is typically 1*cm* to 2*cm* in thickness with a horizontal upper surface. Because clay will change its deformation properties with varying temperature and moisture content, it is important that the conditions of the clay be similar each time a ball drop is performed. Students are asked to minimize the manipulation of the clay by hand, and are directed to use a block of wood to flatten out the clay in preparation for the next ball drop. Data collection is typically conducted over a very short time suggesting that moisture loss due to evaporation isn't a significant concern. Students are also directed to remove water in a pit with a blotter before reshaping the clay. Observing these precautions, this experiment has been conducted several times with good results (e.g., as evidenced in the exponent values of typical graphs). Use of oil-based plasticine might be another way to minimize drying or wetting of the target.

Conducting this lab activity will provide students with an empirical basis for the definition of kinetic energy. It can be used as an opportunity to conduct a simple, yet meaningful, inquiry-oriented lab activity with introductory-level physics students. The activity can be completed in about an hour. Adding this activity to a study of the relationship between the length of a simple pendulum and its period of oscillation allows the author to teach a paradigm lab titled “The Pit and the Pendulum” that has a certain appeal for those familiar with the work of Edgar Allan Poe.

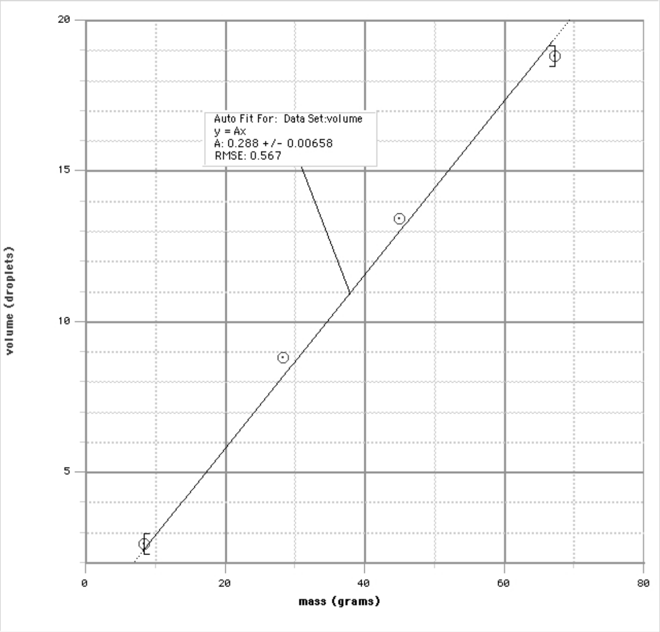

Figure 1. The effect of ball mass on the volume of the pit. The volume of each pit (proportional to the kinetic energy required to produce it) is directly proportional to the mass of the falling ball. A physical model requires the regression line to pass through the origin. These averaged data were collected by parents of elementary school children.

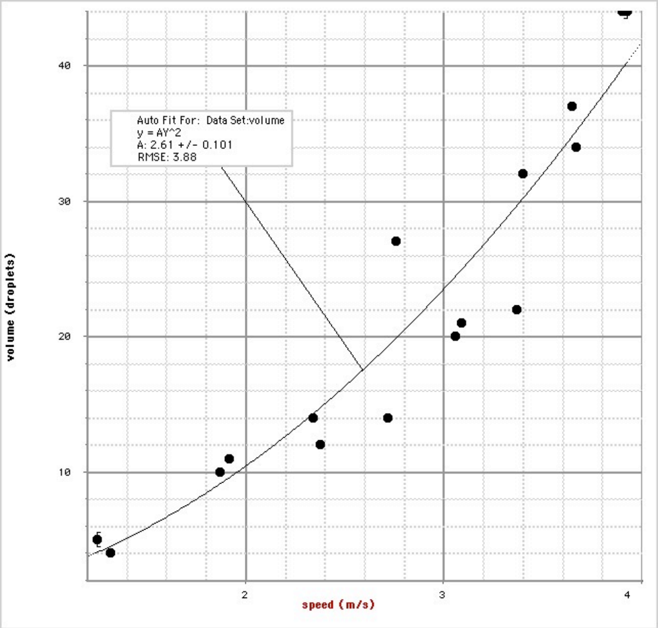

Figure 2. The effect of impact speed on the volume of the pit. The volume of each pit (proportional to the kinetic energy required to produce it) is directly proportional to the speed of the impacting ball squared. A physical model requires the best-fit curve to pass through the origin. These data were collected by 5th through 8th grade school children.

A study of the historic and contemporary issues dealing with science, technology, and society (Easton, 2005) also can help students understand the nature of science, and how science relates to technology and human values. Consider some of the many issues that show the interplay between and among science, technology, and society. Issues dealing with the environment (population, global warming, fossil fuels, nuclear energy), health (pollution, vaccines, pesticides), space (manned flight, near Earth objects, search for extraterrestrial life), society (the war on terror, abortion, euthanasia, human cloning), and ethics (use of animals in research, genetically modified foods), all provide an excellent forum for helping students to understand how science, technology, and society interface and sometimes produce considerable conflict. Addressing these issues (case study discussions, problem-based learning, presentations, research papers, etc.) can help students how to think critically about issues and find ways to solve problems. Approaches such as the above can also help students understand that the world consists of systems of interacting processes and things. Addressing any of the above issues will help students understand how the various parts of systems (subsystems) interface and interact with one another. Such studies can help students understand how things work and allow them to design real-world solutions to problems. By addressing some of the historical and social issues, and studying real-life physical examples, students can learn about modeling complex systems—finding a mathematical relationship between interacting variables. Computer simulations that model real-world situations can also be a powerful tool in helping students understand systems of interacting variables, including both constancy (conservation), change (evolution), and scale.

Directly addressing the history and philosophy of science can help students develop understanding about the nature of science. Addressing such topics as the existence of a universal scientific method, hypothesis generation and theory development, and the contexts of discovery (Hatton & Plouffe, 1997) can all make for enriching classroom experiences.

Why Promote Student Understanding of the Nature of Science?

Why should teachers be concerned with their students understanding the nature of science? Aren't the content and processes of science addressed in an inquiry-oriented course sufficient? Not really. The influence of science on modern society is incalculable. Acid rain, global warming, the energy crises, and "nuclear winter" all challenge each of us to consider the influence of science on society.

Understanding the nature of science—its goals, assumptions, and processes inherent in the development of knowledge—has been one of the major goals of science education since the beginning of the 20th century (Central Association of Science and Mathematics Teachers, 1907). Contemporary literature of the science reform movement also regards understanding the nature of science as one of the main components of science literacy (AAAS, 1993; NRC, 1996).

While a teacher's understanding of the nature of science and an implementation model are necessary prerequisites for teaching about the nature of science (Lederman, 1992), it is not sufficient. Teachers must also value an understanding of the nature of science before they will teach it (Lederman, 1999; Schwartz & Lederman, 2002).

Few individuals will question the value of studying the key concepts of science; however, there are many who might question why we should understand the nature of the scientific process. *Benchmarks for Science Literacy* brings up the following key point about why NOS should be valued, "When people know how scientists go about their work and reach scientific conclusions, and what the limitations of such conclusions are, they are more likely to react thoughtfully to scientific claims and less likely to reject them out of hand or accept them uncritically" (AAAS, 1993, p. 3).

In addition, NOS literacy is important in helping students of science confront the growing amount of pseudoscience that seems to be encroaching upon modern society. It helps them to make informed decisions relating to science-based issues, develop in-depth understandings of science subject matter, and help them to distinguish science from other ways of knowing. (NSTA, 2003) NOS literacy helps students defend themselves against unquestioning acceptance of pseudoscience and reported research (Park, 2000; Sagan, 1996).

The media are filled with hucksters making all sorts of unsubstantiated and unsupportable pseudoscientific claims about fad diets, supposed medical cures, ghosts, alien abductions, psychics, channelers, astrology, intelligent design, mind reading, past life regression therapy, and so on. Students who have a good understanding of the content and nature of science as well as healthy scientific perspectives (e.g., skepticism) will not likely fall prey to flimflam artists who promote technological gadgets of dubious worth, dogmatists who promote beliefs of doubtful credibility, or purveyors of simple solutions to complex problems. NOS literate students will be able to, in Paul DeHart Hurd's words, "distinguish evidence from propaganda, probability from certainty, rational beliefs from superstitions, data from assertions, science from folklore, credibility from incredibility, theory from dogma" (Gibbs & Fox, 1999).

Without expressly addressing the values and assumptions of science, it is highly unlikely that students will come to know them through a process of "osmosis." Early philosophers of science such as Descartes, Galileo, and Newton identified and explained many of the values and assumptions that scientists hold today. One can reasonably conclude that these values and assumptions might never be addressed in a science classroom given the non-controversial atmosphere the normally surrounds the instructional process.

The lack of controversy in modern science instruction does not easily lend itself to the argumentation and values clarification that naturally would help students better understand the nature of science, and distinguish science from other ways of knowing and from pseudoscience. Unfortunately, this lack of controversy also extends beyond the classroom into everyday life. When the masses are confronted with claims of dubious origin, many of these people remain inert. Students who learn through didactic forms of instruction learn to become complacent and accepting of any claims. If students disagree, they mark it up to personal relativism. There is no truth, only opinion.

To really get to know the nature of science, students must engage in the marketplace of ideas. They must learn to use their content knowledge and scientific value systems to identify, confront, and resolve false claims. In a phrase, they must learn to use their "BS" detectors.

An Implementation Model for Achieving NOS Literacy

In addition to possessing an understanding about the nature of science, teachers need to have appropriate models and activities to help their students acquire an adequate understanding of NOS (Abd-El-Khalick et al., 1998; Bell, Lederman & Abd-El-Khalick, 2000). How, then, can teachers successfully promote student understanding in relation to NOS? What pedagogical practices should teachers use in an effort to effectively promote NOS literacy among their students? When does a teacher deal with the subject matter of NOS?

Figure 3 depicts a model that can guide the work of science teachers. The model consists of nine pedagogical practices geared toward helping students attain the required understanding: thematic teaching relates to NOS, background readings that describe NOS, case study discussions that incorporate NOS, inquiry lessons that model NOS, inquiry labs that reflect NOS, problem-based learning incorporates NOS, historical studies that involve NOS, problem-based learning includes NOS, and multiple assessments that address NOS. These approaches will help all students gain a relatively comprehensive understanding of the nature of science. (NOTE TO PANELISTS: Each of the following approaches will be dealt with in detail in other chapters. This chapter is just background that explains in part the rationale for including these practices.)

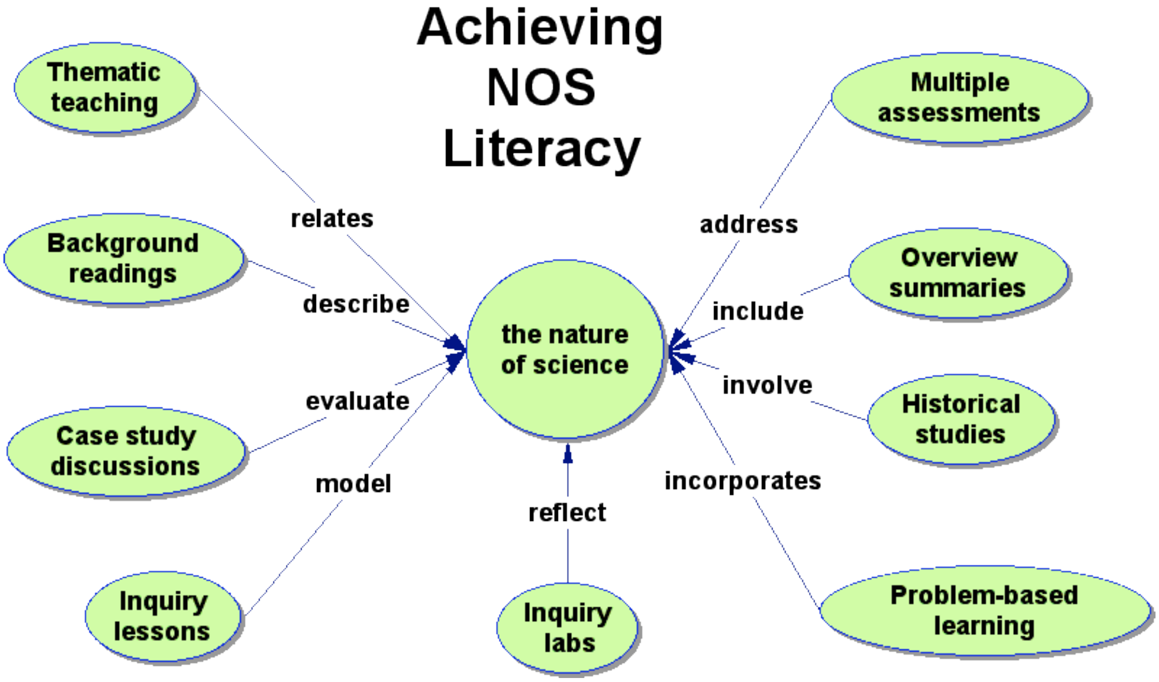

Figure 3. NOS implementation model—pedagogical practices most suited to helping students achieve nature-of science literacy.

Thematic teaching in a physics or physical science course can be a powerful way of including philosophical and historical perspectives in science teaching. For instance, *Physics, the Human Adventure: From Copernicus to Einstein and Beyond* (Holton & Brush, 2001) shows how to integrate science content along with its history and philosophy. Eight strands from this book show how science, history, and philosophy are naturally interwoven: The Origins of Scientific Cosmology, The Study of Motion, Newton's Laws and His System of the Word, Structure and Method in Physical Science, The Laws of Conservation, Origins of the Atomic Theory in Physics and Chemistry, Light and Electromagnetism, and The Atom and the Universe in Modern Physics. If not used as a textbook, at the very least this volume can serve as a reference resource for teachers hoping to improve student understanding of the nature of science. From the perspective of science teaching standards, it is possible to teach science while presenting the subject matter as an intriguing human adventure that has become a major force in our civilization.

Background readings from books and articles that deal directly with the nature of science can have a very significant impact upon a student's understanding of the nature of science. Such readings can also heighten appreciation for science itself. Many books are available that deal reasonably well with the nature of science theme. These might become the basis for classroom literacy circles. Reading the books, discussing them, and writing book reports or book reviews, can provide substantial background that can readily be brought to bear on other classroom discussions. Some suitable books for this endeavor are listed in Table C-4.

Case study discussions (Herreid, 2005) are excellent forums for helping students develop an understanding of NOS. Case studies typically present a dilemma or an issue, and students are asked to help resolve the problem by conducting an analysis of false or doubtful assertions made in the name of science. Case studies need not be of long duration; it's amazing what insights students can gain in relation to NOS with just a 5-minute discussion. Case studies can be used intermittently as a "problem of the day," during pre- and post-lab discussions, and as fillers when extra instructional time presents itself at the end of a class period. The following sidebar story is but one example of a case study.

Table C-4

Recommended Readings List

A list of books from which high school students can select to write a book review.

- *Doubt and Certainty*. Rothman, T. & Sudarshan, G. (1999) New York, NY: Perseus Printers.
- *Fact, Fraud and Fantasy*. Goran, M. (1979) Cranbury NJ: A.S. Barnes and Co., Inc.
- *Fads and Fallacies in the Name of Science*. Gardner, M. (1957) Dover Publications.
- *Great Feuds in Science*. Hellman, H. (1998) New York, NY: John Wiley & Sons, Inc.
- *Science and Its Ways of Knowing*. Hatton, J. & Plouffe, P.B. (1997) Upper Saddle River, NJ: Prentice Hall.
- *Scientific Literacy and the Myth of the Scientific Method*. Bauer, H.H. (1994) Urbana, IL: University of Illinois Press.
- *The Borderlands of Science: Where Sense Meets Nonsense*. Shermer, M. (2001) Cambridge: Oxford University Press.
- *The Demon Haunted Word: Science as a Candle in the Dark*. Sagan, C. (1996) New York, NY: Ballantine Books.
- *The Game of Science*. McCain, G. & Segal, E.M. (1989) Belmont, CA: Brooks/Cole

Publishing Co.

- *Uncommon Sense: The Heretical Nature of Science*. Cromer, A. (1993) New York, NY: Oxford University Press.
- *Voodoo Science: The Road from Foolishness to Fraud*. Park, R.L. (2000) Cambridge: Oxford University Press.
- *Why People Believe Weird Things*. Shermer, M. (1997) New York: W. H. Freeman and Co.

Sidebar Story 4—Pulsing Red LED Light Gives Relief?

Recently (Autumn 2007), there has been a television commercial about a product known as Light Relief™ . The Light Relief™ device appears to be made out of several dozen pulsing red light emitting diodes in a unit that conforms to the hand. The TV advertisement shows a person waiving a Light Relief™ unit over but not touching arms, hands, shoulders, and legs, noting that it will give "relief." The company's website (LightRelief.com) states, "Experience the healing power of Light Relief." The general claim is therefore made that Light Relief™ can provide relief and healing, but to what maladies it is not clear. No specific medical claims are made. Nonetheless, the website notes, "If, within 30 days of receiving Light Relief™ , you are not thrilled with your results, simply return it for a complete refund of your purchase price (less shipping and processing)." Imagine that a person purchases such a unit and uses it for 30 days. At the end of 30 days a friend asks, "Do you receive any relief?" The consumer says, "Yes, absolutely!"

- What, if anything, is wrong with the promotion the Light Relief™ ?
- Does the fact that no specific medical claims are made justify this unit's promotion and sale?
- From a scientific perspective, what is wrong if anything with a consumer's anecdotal claim of efficacy of Light Relief™ ?
- What do you think the sellers of Light Relief™ believe about the nature of their prospective customers?

Claims like the one in the sidebar story #4 about Light Relief™ abound on cable television and in print media. They are all suitable for case study analysis. It's not uncommon to see Arthur P. Johnson talking about his "treasury of health secrets" or Kevin Trudeau talking about "natural cures" when surfing the channels or perusing the selves of the local bookstore. Junk science and pseudo science are a fertile ground for case studies. Topics as diverse as ancient astronauts, astrology, the Bermuda triangle, biorhythms, blood type diet, creationism, *Dianetics,* hollow earth, full moon myths, mesmerism, orgone energy, parapsychology, rake therapy, scientology, spontaneous human combustion, and subliminal advertising. While these topics are not the subject matter of a physics course per se, they can be brought in as short-term case studies that help students distinguish science from things so called.

As has been shown, Popper and Hume have provided us with a solid if not definitive basis for evaluating scientific claims. In addition, Parker (2000) gave a set of criteria that can be used in case study discussions where dubious scientific claims are made. He presented "seven warning signs of bogus science" that might be used by students to determine if a claim lies well outside the bounds of rational scientific discourse. He cautions that some legitimate claims might well possess one or more of the following indicators:

1. The discoverer pitches the claim directly to the media.
2. The discoverer says that a powerful establishment is trying to suppress his or her work.
3. The scientific effect involved is always at the very limit of detection.
4. Evidence for a discovery is anecdotal.
5. The discoverer says a belief is credible because it has endured for centuries.
6. The discoverer has worked in isolation.
7. The discoverer must propose new laws of nature to explain an observation.

Inquiry lessons, as one of the levels of the "inquiry spectrum" (Wenning, 2005a), provide an excellent forum for student learning in relation to NOS. Inquiry lessons by their very nature are predisposed to modeling science processes. As teachers conduct inquiry lessons, they can use "think aloud" protocols to provide insights about the workings of science; they can guide student thinking through focusing questions; they can talk explicitly about procedures being employed; they can give explicit instruction while modeling scientific inquiry practices. Inquiry lessons are a great way to teach NOS both explicitly and implicitly.

Inquiry labs, as opposed to traditional cookbook labs (Wenning, 2005a), help students learn and understand the intellectual processes and skills of scientists, and the nature of scientific inquiry. Inquiry labs are driven by questions requiring ongoing intellectual engagement, require the use higher-order thinking skills, focus students' attention on collecting and interpreting data, and help them discover new concepts, principles, or laws through the creation and control their own experiments. With the use of inquiry labs, students employ procedures that are much more consistent with the authentic nature of scientific practice. With inquiry labs, students learn such things as nomenclature and process skills, and do so implicitly. Pre- and post-labs provide opportunities for explicit instruction about NOS.

Problem-based learning (PBL) is a form of curriculum that deals with both the content and processes of what is to be learned. It is an instructional approach that helps students to become active problem solvers using a "messy" real-world problem for which there is no ready solution. Examples of issues-based activities would be placement of a nuclear power plant or low-level nuclear waste dump in a community, development of a wind farm, including creation science or intelligent design in the science classroom. PBLs dealing with such issues—where students are required to take one of two sides either for or against an issue—will provide yet another opportunity for students to conduct a critical analysis of a real-world issue.

Properly implemented, a PBL activity can build multidisciplinary knowledge, integrate knowledge from a variety of disciplines, assist in values clarification, help students see the utility of many disciplines, and help students apply what they know about subject matter to real-life situations.

The PBL approach places students in active roles as problem solvers. The approach confronts students with a complex problem that does not necessarily have a single best answer. The problem-solving process will be messy and complex, just like in the real world. A solution of the problem will require students to inquire into the stated problem, gather information, and reflect upon the findings. The solution will always be tentative and changing as more information is obtained and internalized. Students working in small groups will frequently find that they are required to state and defend their conclusions on the basis of evidence and argumentation. This provides students with both a challenge and motivation. Good PBL problems will always require students to learn both in depth and in breadth before they will be able to provide meaningful, practical solutions to the real-world problem provided. A good PBL statement will appeal to the human desire for a resolution, and thereby sets up the needed context for learning. The problem necessarily should be based on desired outcomes, learner characteristics, compelling situations, and suitable resources.

Sidebar Story 5—A Sample PBL

A commission has been established by the Governor to address the energy future of the State of Illinois. With continuing population growth, growing pollution, global warming, and dwindling traditional energy sources such as oil and natural gas, the commission has been charged with charting a vision for Illinois' energy future. Four energy consortiums have been hired as consultants to "make the case" for building capacity in each of four different areas to supplant or augment traditional energy sources:

- Wind
- Coal
- Nuclear
- Hydroelectric

Your consulting firm's goal is to literally make the case for your form of energy source before the Governor's commission; nonetheless, drawbacks of other energy sources should be addressed in the commission hearing. There are many questions and issues associated with determining the best path for the future of Illinois:

- Cost of site and facility development
- Production and delivery cost per kilowatt hour
- Environmental impact
- Economic impact
- Availability of proven technology
- Quality of life issues
- Safety issues
- Size of source and sustainability

Consulting Team and Individual Tasks: As a member of one of the consulting teams you need to do the following:

- conduct research addressing each of the questions and issues outlined above
- conduct-to-benefit analysis in the issues areas, identifying and addressing all major concerns
- conduct a risk analysis as appropriate
- explain how, when, and where the energy facility would be developed
- identify and address false or doubtful claims made by the opposition in the name of science.

Historical studies can help students understand the nature of science. These perspectives can prove to be a powerful tool for not only teaching about NOS, but for putting a human face on physics and increasing student interest in the subject. The *National Science Education Standards* suggest the use of history “to elaborate various aspects of scientific inquiry, the nature of science, and science in different historical and cultural perspectives” (NRC, 1996, p. 200). The components of *NSES* dealing with history and the nature of science are closely aligned with similar standards described in Project 2061's *Benchmarks for Science Literacy*. *Benchmarks* notes, "There are two principal reasons for including some knowledge of history among the recommendations. One reason is that generalizations about how the scientific enterprise operates would be empty without concrete examples. A second reason is that some episodes in the history of scientific endeavor are of surpassing significance to our cultural heritage" (AAAS, 1993, p. 237). Each of the sciences has at least one "great idea" that can be used to incorporate the historical perspective: Physics—models of the atom, gas, or light; Chemistry— periodic table of elements; Biology—evolution; Earth Science—plate tectonics; and Space Science—nature of the solar system and/or Big Bang.

Table C-5

Historical Perspectives

Some historical perspectives that might be included in the course of physics teaching per Benchmarks 10a-j.

- Displacing the Earth from the Center of the Universe: Movement from geocentrism to heliocentrism including scientific arguments for the annual and daily motions of the Earth. Includes references to Aristotle, Ptolemy, Copernicus, Kepler, and Galileo
- Uniting Heavens and Earth: The Newtonian synthesis, how a study of the moon's acceleration in comparison to that of those things near the surface of the Earth led to Newton's formulation of gravity
- Relating Matter & Energy and Time & Space: Addressing the work of Einstein and its relationship to that of Newton
- Splitting the Atom: A study of radioactivity from its discovery to its impact on world affairs. Includes work of the Curies, Rutherford, Meitner, Fermi, and others
- Harnessing Power: Work and energy

Overview summaries, a “re-presentation” of subject matter with insights and reflections provided by the teacher and conducted near or at the end of a unit, can serve several purposes: (a) helping students to review, relearn and retain the subject matter of the unit, (b) helping students understand the nature of science by taking a metacognitive overview of what was learned and how it was learned, (c) helping students draw connections between the subject matter studied and the real world aiding with transfer, and (d) helping students see the interconnections between the sciences through their unifying concepts.

Multiple assessments, alternative as well as more traditional, are important components in helping students to develop a deeper understanding of the nature of science. Alternative assessments such as written analysis of false or misleading claims, research-based presentations dealing with historical/philosophical subject matter, and periodic reflective journaling can be good ways to heighten student understanding of NOS. Test items such as multiple-choice and free-response questions on traditional exams can get students to focus attention and study time on the nature of science. Students tend to study those things that are addressed during assessment, and for which they are held accountable. A set of student performance objectives should be developed in relation to NOS goals, and students should be made aware of them. Lessons and assessments then should be aligned with these objectives.

Nature of Science and the Scientific Enterprise

The nature of science, as played out in its history and philosophy, is suitable subject matter for study at all grade levels. Students, at all levels, need to understand that science is both a product and a process. Little is gained when we teach students in a dogmatic way—on the basis of authority. Such instruction can be a great disservice to the scientific community when students (especially later as adults) see scientific ways of knowing on par with other ways of knowing—when scientific knowledge is seen as just one more opinion among many.

The scientific worldview is "subtle," and its assumptions, values, and limitations are not things that are always easily taught. Scientific knowledge, for instance, while being durable, is also tentative and subject to revision. Science taught on the basis of authority alone rarely does much to help students understand this point. Only when they possess a clear understanding of the nature of science and of scientific knowledge do students come to realize this point.

Benchmarks for Science Literacy (AAAS, 1993), in describing the importance of helping students develop a scientific worldview, points out that students at different grade levels should learn differently. It points out that younger children are more interested in science than the philosophy of science but, nonetheless, they should come to know certain things by the time they reach the end of 8th grade:

- When similar investigations give different results, the scientific challenge is to judge whether the differences are trivial or significant, and it often takes further studies to decide. Even with similar results, scientists may wait until an investigation has been repeated many times before accepting the result as correct.

- Scientific knowledge is subject to modification as new information challenges prevailing theories and a s new theory leads to looking at old observations in a new way.

- Some scientific knowledge is very old and yet is still applicable today.

- Some matters cannot be examined usefully in a scientific way. Among them are matters that by their very nature cannot be tested objectively and those that are

> essentially matters of morality. Science can sometimes be used to inform ethical decisions by identifying the likely consequences of particular actions but cannot be used to establish that some action is either moral or immoral.

Benchmarks also points out that by the end of 12th grade, students should know that:

- Scientists assume that the universe is a vast single system in which the basic rules are the same everywhere. The rules may range from very simple to extremely complex, but scientists operate on the belief that the rules can be discovered by careful, systematic study.
- From time to time, major shifts occur in the scientific view of how the world works. More often, however, the changes that take place in the body of scientific knowledge are small modifications of prior knowledge. Change and continuity are persistent features of science.
- No matter how well one theory fits observations, a new theory might fit them just as well or better, or might fit a wider range of observations. In science, the testing, revision, and occasional discarding of theories, new and old, never ends. This ongoing process leads to an increasingly better understanding of how things work in the world but not to absolute truth. Evidence for the value of this approach is given by the improving ability of scientists to offer reliable explanations and make accurate predictions.

The scientific enterprise itself is also suitable subject matter for study at all grade levels. By the time students complete 8th grade they should know that peoples of all races, ethnic backgrounds, and sex have contributed to the development of science, that knowledge and technology resulting from the scientific enterprise are available to people around the word, that scientist work in many different settings, and scientists are obliged to follow rules of ethical behavior when doing research. By the time students complete 12th grade they should also know that science is influenced by society and technology, that different sciences have different ways of conducting research, and that science can be used to inform public policies and processes. Details about these and other factors relating to the scientific enterprise can be pursued through a careful reading of *Benchmarks*.

Helping students understand the nature of science—by addressing its content, history and philosophy—allows them to see science as a human endeavor. This endeavor relies strongly on basic human skills such as reasoning, problem solving, energy, insight, passion, and creativity. It also focuses attention on critical habits of mind we hope to instill among our students – objectivity, skepticism, intellectual honesty, openness to new ideas, and reasoned tolerance of ambiguity. Only by pointing out historical examples and providing philosophical underpinnings can student come to value these traits as well.

As John Dewey noted when writing for the journal *Science* in 1910, "Science teaching has suffered because science has been so frequently presented just as so much ready-made knowledge, so much subject-matter of fact and law, rather than as the effective method of inquiry into any subject-matter." Generations of students have also suffered from this narrow and shortsighted perspective on science. Whenever science is taught this way, it shortchanges students and perhaps most especially girls. Girls tend to perceive science as lacking a human element and frequently show less interest as a result (AAUW, 1992).

Table C-6

Belief Statements Assumed to be Important in Achieving NOS Literacy

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- **Teachers** can pass on to their students only what they themselves possess. Teachers must therefore possess an understanding of the nature of science if they are to impart that understanding to their students.
- **Teachers** must understand that NOS is suitable subject matter for student study in the science classroom.
- **Teachers** must value NOS literacy before they will impart that understanding to their students. An understanding of NOS alone is not enough to make teachers to value or teach it.
- **Teachers** must be provided with an effective and practical means of achieving NOS literacy among their students before they will make the attempt to do so. To this end we deploy the implementation model described in this article.

- **Teachers** tend to teach the way in which they themselves were taught. It is only reasonable, therefore, that we should teach in the way that we expect our candidates to teach, and this includes considerations for the nature of science.

Practical Advice for Implementing NOS Instruction

Based on a review of the literature, experience, and philosophical reflections, the following advice is offered for implementing instruction in relation to NOS: (1) *The nature of science is best taught explicitly to both teacher candidates and students of science*. Research has shown that students fail to develop many of the expected understandings of NOS concepts from traditional classroom instruction where it is assumed that students will learn about the nature of science by "osmosis" (Duschl, 1990; Lederman, 1992; Ryan & Aikenhead, 1992). NOS, therefore, should be taught explicitly when possible to develop the desired understandings (Bell, Blair, Crawford & Lederman, 2003; Khishfe & Abd-El- Khalick, 2002; Moss, Abrams & Robb, 2001; Abd-El-Khalick & Lederman, 2000; Akerson, Abd-El-Khalick & Lederman, 2000). Without directly addressing scientific nomenclature, intellectual process skills, rules of scientific evidence, postulates of science, scientific dispositions, and major misconceptions about science, it is highly unlikely that students will extract all these concepts on their own.

Experience shows that after several years of didactic science instruction, many science majors end up with only a vague and fragmented understanding of the nature of science. (2) *The nature of science is best taught contextually*. Students can develop a functional understanding of the nature of science only when they are taught in the context of scientific inquiry. NOS should not be treated as subject matter apart from the content of science, be it physics, chemistry, biology, earth and space science, or environmental science. (3) *The nature of science is best taught experientially*. Teaching science through inquiry helps student understand the nature of the scientific endeavor that simply cannot be meaningfully obtained in any other fashion. (4) *The nature of science is best taught regularly*. Addressing the nature of science once or twice, even if is dealt with as part of a discrete unit, is inadequate to the task of teaching students about NOS. Only repeated treatment of the subject matter of NOS covering a wide variety of situations will imbue students with a proper understanding. (5) *The nature of science is best taught systematically*. Teachers ought to know what should be taught in relation to this topic, and address the whole range of information about NOS with their students. To teach the subject haphazardly will result in substantial gaps in student understanding. (6) *Only by helping teachers focus on the nature of science as an important goal in their instructional practice will result in more explicit science instruction* (Lederman, Schwartz, Abd-El-Khalick & Bell, 2001).

References

Abd-El-Khalick, F., Bell, R., & Lederman, N. G. (1998). The nature of science and instructional practice: Making the unnatural natural. *Science Education, 82*(4), 417-436.

Abd-El-Khalick, F., & Lederman, N. G. (2000). Improving science teachers' conceptions of the nature of science: A critical review of the literature. *International Journal of Science Education, 22,* 665-701.

Akerson, V.L., Abd-El-Khalick, F., & Lederman, N. G. (2000). Influence of a reflective explicit activity-based approach on elementary teachers' conceptions of nature of science. *Journal of Research in Science Teaching, 37,* 295-317.

Aldridge, J. M., Taylor, P. C., & Chen, C., (1997). *Development, validation, and use of the Beliefs About Science and School Science Questionnaire (BASSSQ).* Paper presented at the National Association for Research in Science Teaching, (NARST), Chicago, Illinois.

Alters, B. J. (1997). Whose nature of science? *Journal of Research in Science Teaching, 34,* 39-56. American Association for the Advancement of Science (1989). *Science for All Americans*. Washington, DC: Author.

American Association for the Advancement of Science (1989). *Science for all Americans*. Washington, DC: Author.

American Association for the Advancement of Science (1993). *Benchmarks for Science Literacy*. Washington, DC: Author.

American Association of University Women (1992). The AAUW Report: How schools shortchange girls. Washington, DC: Author.

Bakker, G., & Clark, L. (1988). *Explanation: An Introduction to the Philosophy of Science*. Mountain View, CA: Mayfield Publishing Company.

Bell, R., Blair, L., Crawford, B. & Lederman, N.G. (2003). Just do it? The impact of a science apprenticeship program on high school students' understandings of the nature of science and scientific Inquiry. *Journal of Research in Science Teaching, 40,* 487-509.

Bell, R. L., Lederman, N. G. & Abd-El-Khalick, F. (2000). Developing and acting upon one's conception of the nature of science: A follow-up study. *Journal of Research in Science Teaching, 37,* 563-581.

Central Association of Science and Mathematics Teachers (1907). A consideration of the principles that should determine the courses in biology in the secondary schools. School Science and Mathematics, 7, 241-247.

Curd, M., & Cover, J. A. (1998). *Philosophy of Science: The Central Issues*. New York: W. W. Norton & Co., Inc.

Duschl, R.A. (1990). *Restructuring Science Education*. New York: Teachers College Press.

Easton, T. A. (2005). *Taking Sides: Clashing Views on Controversial Issues in Science, Technology, and Society*. Dubuque, IA: McGraw-Hill/Dushkin.

Gibbs, W. W., & Fox, D. (1999). The false crisis in science education. *Scientific American, 281,* 87-93.

Hirsch, E. D., Jr. (1987). *Cultural Literacy: What Every American Needs to Know*. Boston, MA: Houghton Mifflin Company.

Holton, G., & Brush, S.G. (2001). Physics, the human adventure: From Copernicus to Einstein and beyond, New Brunswick, NJ: Rutgers University Press.

Khishfe, R., & Abd-El-Khalick, F. (2002) Influence of explicit and reflective versus implicit inquiry-oriented instruction on sixth graders' views of nature of science. *Journal of Research in Science Teaching, 39,* 551-578.

Klee, R. (1997). *Introduction to the Philosophy of Science: Cutting Nature at its Seams.* New York: Oxford University Press.

Labinger, J. A., & Collins, H. (Eds.). (2001) *The One Culture?* Chicago: University of Chicago Press.

Laudan, L. (1990). *Science and Relativism: Some Key Controversies in the Philosophy of Science*. Chicago: University of Chicago Press.

Lederman, N. G. (1992). Students' and teachers' conceptions of the nature of science: A review of the research. *Journal of Research in Science Teaching, 29,* 331-359.

Lederman, N. G. (1999). Teachers' understanding of the nature of science and classroom practice: Factors that facilitate or impede the relationship. *Journal of Research in Science Teaching, 36,* 916-929.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of the nature of science questionnaire: Toward valid and meaningful assessment of learner's conceptions of the nature of science. *Journal of Research in Science Teaching, 39*(6), 497-521.

Lederman, N. G., Schwartz, R. S., Abd-El-Khalick, F, & Bell, R. L. (2001). Preservice teachers' understanding and teaching of the nature of science: An intervention study. *Canadian Journal of Science, Mathematics, and Technology Education, 1*(2), 135-160.

McComas, W. F. (1996). Ten myths of science: Reexamining what we think we know... *School Science & Mathematics, 96,* 10-16.

McComas, W. F, Clough, M. P., & Almazroa, H. (1998). The role and character of the nature of science in science education. *Science & Education, 7,* 511-532.

Moss, D. M., Abrams, E. D., & Robb, J. (2001). Examining student conceptions of the nature of science. *International Journal of Science Education, 8,* 771-790.

National Research Council. (1996). *National Science Education Standards*. Washington DC: National Academies Press.

Park, R. L. (2000). *Voodoo science: The road from foolishness to fraud*. New York, NY: Oxford University Press.

Ryan, A. G., & Aikenhead, G. S. (1992) Students' preconceptions about the epistemology of science. *Science Education, 76,* 559-580.

Sagan, C. (1996). *The Demon-Haunted World. Science as a Candle in the Dark*. New York, NY: Ballantine Books.

Schwartz, R. S., & Lederman, N. G. (2002). "It's the nature of the beast": The influence of knowledge and intentions on learning and teaching nature of science. *Journal of Research in Science Teaching, 39,* 205-236.

Stigler, J. W. & Hiebert, J. (1999). *The Teaching Gap: Best Ideas from the World's Teachers for Improving Education in the Classroom*. New York: The Free Press.

Wenning, C. J. (2005a). Levels of inquiry: Hierarchies of pedagogical practices and inquiry processes. *Journal of Physics Teacher Education Online, 2*(3), 3-11.

Wenning, C. J. (2005b). Implementing inquiry-based instruction in the science classroom: A new model for solving the improvement-of-practice problem. *Journal of Physics Teacher Education Online, 2*(4), 9-15.

Wenning, C. J. (2005c). Minimizing resistance to inquiry-oriented instruction: The importance of climate setting. *Journal of Physics Teacher Education Online, 3*(2), 10-15.

Wenning, C. J., & Wenning, R. E. (2006). A generic model for inquiry-oriented labs in postsecondary introductory physics *Journal of Physics Teacher Education Online, 3*(3), 24-33.