THE PRINCIPAL ELEMENTS OF THE NATURE OF SCIENCE: DISPELLING THE MYTHS

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The "myths of science" discussed here are commonly included in science textbooks, in classroom discourse and in the minds of adult Americans. These fifteen issues, described here as "myths of science," do not represent all of the important issues that teachers should consider when designing instruction relative to the nature of science, but may serve as starting points for evaluating current instructional foci while enhancing future curriculum design. Misconceptions about science are most likely due to the lack of philosophy of science content in teacher education programs and the failure of such programs to provide real science research experiences for preservice teachers while another source of the problem may be the generally shallow treatment of the nature of science in the textbooks to which teachers might turn for guidance. Some of these myths, such as the idea that there is a scientific method, are most likely caused by the explicit inclusion of faulty ideas in textbooks while others, such as lack of knowledge of the social construction of scientific knowledge, are the result of omissions in texts.

As Steven Jay Gould points out in *The Case of the Creeping Fox Terrier Clone* (1988), science textbook writers are among the most egregious purveyors of myth and inaccuracy. The "fox terrier" refers to the classic comparison used to express the size of the dawn horse, tiny precursor to the modern horse. This comparison is unfortunate for two reasons. Not only was this horse ancestor much bigger than a fox terrier, but the fox terrier breed of dog is virtually unknown to American students. The major criticism leveled by Gould is that once this comparison took hold, no one bothered checking its validity or utility. Through time, one author after another simply repeated the inept comparison and continued a tradition making many science texts virtual clones of each other on this and countless other points.

In an attempt to provide a more realistic view of science and point out issues on which science teachers should focus, this chapter presents and discusses fifteen widely held, yet incorrect ideas about the nature of science. There is no implication that all students, or most teachers for that matter, hold all of these views to be true, nor is the list meant to be the definitive catalog. Cole (1986) and Rothman (1992) ave suggested additional misconceptions worthy of consideration. However, years of science teaching and the review of countless texts has substantiated the validity of the following inventory presented here.

MYTH 1: HYPOTHESES BECOME THEORIES THAT IN TURN BECOME LAWS

This myth deals with the general belief that with increased evidence there is a developmental sequence through which scientific ideas pass on their way to final acceptance (see Figure 1) as mature laws. The implication is that hypotheses and theories are less secure than laws. A former U.S. president expressed his misunderstanding of science by saying that he was not troubled by the idea of evolution because it was, in his words, "just a theory." The president's misstatement is the essence of this myth; an idea is not worthy of consideration until "lawness" has been bestowed upon it.

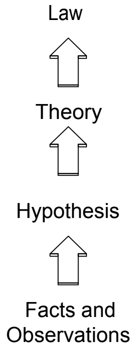

Figure 1. The false hierarchical relationship between facts, hypotheses, theories and laws.

Theories and laws are very different kinds of knowledge, but the misconception portrays them as different forms of the same knowledge construct. Of course there is a relationship between laws and theories, but it is not the case that one simply becomes the other -- no matter how much empirical evidence is amassed. Laws are generalizations, principles or patterns in nature and theories are the explanations of those generalizations (Rhodes and Schaible, 1989; Horner and Rubba, 1979; Campbell, 1953). Dunbar (1995) addresses the distinction in a very useful fashion by calling laws "cookbook science," and the explanations "theoretical science." He labels the multiple examples of the kind of science practiced by traditional peoples as "cookbook" because those who apply the rules after observing the patterns in nature do not understand why nature operates in the fashion that it does. The rules work and that is enough.

Even in more sophisticated settings, cookbook science is occasionally practiced. For example, Newton described the relationship of mass and distance to gravitational attraction between objects with such precision that we can use the law of gravity to plan space flights. During the Apollo 8 mission, astronaut Bill Anders responded to the question of who was flying the spacecraft by saying, "I think Isaac Newton is doing most of the driving right now" (Chaikin, 1994, p. 127). His response was understood to mean that the capsule was simply following the basic laws of physics described by Isaac Newton centuries earlier.

The more thorny, and many would say more interesting, issue with respect to gravity is the explanation for why the law operates as it does. At this point, there is no well-accepted theory of gravity. Some physicists suggest that gravity waves are the correct explanation, but with clear confirmation and consensus lacking, most feel that the theory of gravity still eludes science. Interestingly, Newton addressed the distinction between law and theory with respect to gravity. Although he had discovered the law of gravity, he refrained from speculating about its cause. In *Principia*, Newton states " . . . I have not been able to discover the cause of those properties of gravity from phenomena, and I frame no hypothesis . . ." " . . . it is enough that gravity does really exist, and act according to the laws which we have explained . . ." (Newton, 1720/1946, p. 547).

MYTH 2: SCIENTIFIC LAWS AND OTHER SUCH IDEAS ARE ABSOLUTE

This myth involves two elements. First, even if individuals understand that scientific laws are equal in importance to theories, they rarely appreciate that all knowledge in science is tentative, occasionally seeing "proof" in science equal to proof in mathematics. The issue of tentativeness is part of the self-correcting aspect of science but one that those who fault science frequently ignore. Creationists, for instance, are quick to criticize science by pointing to the discovery of several teeth found in Nebraska early in this century (Gould, 1991). Initially, these teeth were considered to have come from a primitive human, but were later found to be those of an extinct pig. Scientists made both the initial identification and the later revision, but those who would like to fault science only discuss the error, while rarely mentioning the inevitable correction.

Another aspect of this myth stems from the realization that there are several basic kinds of laws — deterministic and probabilistic. Although both types of laws are as tentative as any scientific knowledge, the laws of the physical sciences are typically deterministic in that cause and effect are more securely linked while the laws in biology usually have a probability factor associated. In the life sciences it is typical to see limitations placed on the application of laws. For example, Mendel's laws of inheritance work only with single gene pairs and not even with all such pairs. This issue has called some to question if there are really laws in biology. My response would be that there are laws in the life sciences, but the rules for their application are somewhat distinct from those applied in the physical sciences.

MYTH 3: A HYPOTHESIS IS AN EDUCATED GUESS

The definition of the term hypothesis has taken on an almost mantra-like life of its own in science classes. If a hypothesis is always an educated guess as students typically assert, the question remains, "an educated guess about what?" The best answer for this question must be, that without a clear view of the context in which the term is used, it is impossible to tell.

The term hypothesis has at least three definitions, and for that reason, should be abandoned and replaced, or at least used with caution. For instance, when Newton said that he framed no hypothesis as to the cause of gravity he was saying that he had no speculation about an explanation of why the law of gravity operates as it does. In this case, Newton used the term hypothesis to represent an immature theory.

As a solution to the hypothesis problem, Sonleitner (1989) suggested that tentative or trial laws be called generalizing hypotheses with provisional theories referred to as explanatory hypotheses. Another approach would be to abandon the word hypothesis in favor of terms such as speculative law or speculative theory. With evidence, generalizing hypotheses may become laws and speculative theories become theories, but under no circumstances do theories become laws. Finally, when students are asked to propose a hypothesis during a laboratory experience, the term now means a prediction. As for those hypotheses that are really forecasts, perhaps they should simply be called what they are, predictions.

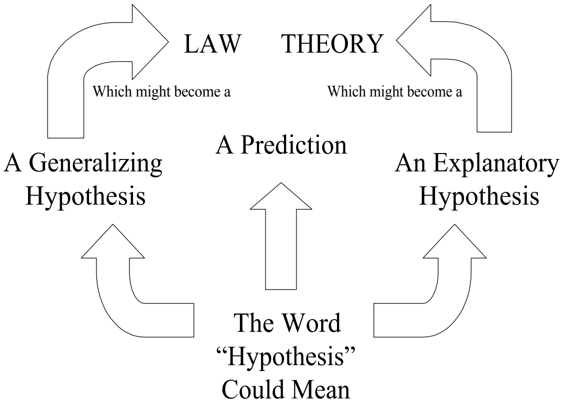

Figure 2. "Family tree" of hypotheses, illustrating the multiple definitions of the term.

MYTH 4: A GENERAL AND UNIVERSAL SCIENTIFIC METHOD EXISTS

The notion that a common series of steps is followed by all research scientists must be among the most pervasive myths of science given the appearance of such a list in the introductory chapters of many precollege science texts. The steps listed for the scientific method vary somewhat from text to text but usually include: a) defining the problem, b) gathering background information, c) forming a hypothesis, d) making observations, e) testing the hypothesis and f) drawing conclusions. Some texts conclude their list of the steps by listing communication of results as the final ingredient as illustrated in Figure 3.

7. Report Results
6. Form Conclusions
5. Test the Hypothesis
4. Make Relevant Observations
3. Form a Hypothesis
2. Gather Information
1. Define the Problem

Figure 3. The typical steps associated with the so-called scientific method.

The universal scientific method is one of science educations' most pervasive "creeping fox terriers." The multi-step list seems to have started innocently enough when Keeslar (1945a b) prepared a list of a number of characteristics associated with scientific research such as establishing controls, keeping accurate records, making careful observations and measurements. This list was refined into a questionnaire and submitted to research scientists for validation. Items that were highly ranked were put in a logical order and made part of the final list of elements associated with the investigation of scientific problems. Textbook writers quickly adopted this list as *the* description of how science is done. In time the list was reduced from ten items to those mentioned above, but in the hands of generations of textbook writers, a simple list of characteristics associated with scientific research became a description of how all scientists work.

Another reason for the widespread belief in a general scientific method may be the way in which results are presented for publication in research journals. The standardized style makes it appear that scientists follow a standard research plan. Medawar (1991) reacted to the common style exhibited by research papers by calling the scientific paper a fraud since the final journal report rarely outlines the actual way in which the problem was investigated.

Those who study scientists at work have shown that no research method is applied universally (Carey, 1994; Gibbs and Lawson, 1992; Chalmers, 1990 and

Gjertsen, 1989). The notion of a single scientific method is so pervasive that many students must be disappointed when they discover that scientists do not have a framed copy of the steps of the scientific method posted above each laboratory workbench.

Close inspection will reveal that scientists approach and solve problems with imagination, creativity, prior knowledge and perseverance. These, of course, are the same methods used by all effective problem-solvers. The lesson to be learned is that science is no different from other human endeavors when puzzles are investigated. Fortunately, this is one myth that may eventually be displaced since many newer texts are abandoning or augmenting the list in favor of discussions of *methods* of science.

MYTH 5: EVIDENCE ACCUMULATED CAREFULLY WILL RESULT IN SURE KNOWLEDGE

All investigators, including scientists, collect and interpret empirical evidence through the process called induction. This is a technique by which individual pieces of evidence are collected and examined until a law is discovered or a theory is invented. Useful as this technique is, even a preponderance of evidence does not guarantee the production of valid knowledge because of what is called the problem of induction.

Frances Bacon first formalized induction in the 17th century. In his 1620 book, *Novum Organum*, Bacon advised that facts should be assimilated without bias to reach a conclusion. The method of induction he suggested is in part the principal way by which humans traditionally have produced generalizations that permit predictions. Baconian induction, and the related process of deduction (or hypothetico-deductivism) is illustrated in Figure 3. Without the creative leap (shown later in Figure 4), the process of Baconian induction is most accurately characterized as naive induction.

The problem with induction is that it is both impossible to make all observations pertaining to a given situation and illogical to secure all relevant facts for all time, past, present and future. However, only by making all relevant observations throughout all time, could one say that a final valid conclusion had been made. On a personal level, this problem is of little consequence, but in science the problem is significant. Scientists formulate laws and theories that are supposed to hold true in all places and for all time but the problem of induction makes such a guarantee impossible. This problem is particularly acute in biology and to some extent in geology. The laws of biology for instance, are confined at the moment to the only planet on which they have been tested. It is unlikely that the rules of the life sciences, as we know them, would, in fact, operate on other planets where life has evolved.

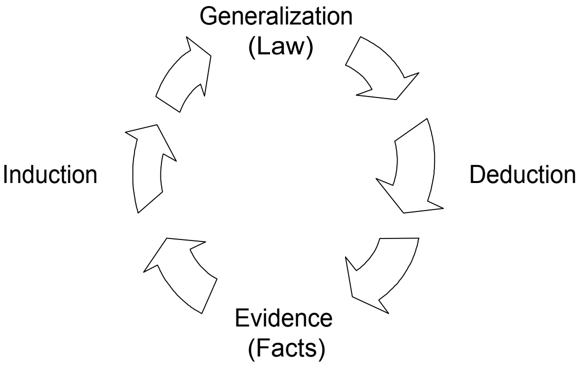

Figure 4. A typical view of Baconian knowledge production. Bacon's view (on the left) of the production of new generalizations and deduction, or hypothetico-deductivism (on the right) for the testing of such generalizations. The diagram does not imply that the laws produce new facts, but rather that a valid law would permit the accurate prediction of facts not yet known.

The proposal of a new law begins through induction as facts are heaped upon other relevant facts. Deduction is useful in checking the validity of a law. For example, if we postulate that all swans are white, we can evaluate the law by predicting that the next swan found will also be white. If it is, the law is supported (but not proved as we discuss). Locating a black swan will cause the law to be questioned.

The nature of induction itself is another interesting aspect associated with this myth. If we set aside the problem of induction momentarily, there is still the issue of how scientists make the final leap from the mass of evidence to the conclusion. In an idealized view of induction, the accumulated evidence will simply result in the production of a new law or theory in a procedural or mechanical fashion. In reality, there is no such method. The issue is far more complex and interesting than that. The final creative leap from evidence to scientific knowledge is the focus of another myth of science. (See Figure 4).

MYTH 6: SCIENCE AND ITS METHODS PROVIDE ABSOLUTE PROOF

The general success of the scientific endeavor suggests that its products must be valid. However, a hallmark of science is that it is subject to revision when new information is presented. Tentativeness resulting in a lack of dogmatism is one of the points that differentiates science from other forms of knowledge. Accumulated evidence can provide support, validation and substantiation for a law or theory, but will never prove those laws and theories to be true. This idea has been addressed well by Horner and Rubba (1978) and Lopushinsky (1993).

The problem of induction argues against proof in science, but there is another element of this myth worth exploring. In actuality, the only truly conclusive knowledge produced by science results when a notion is falsified. What this means is that no matter what scientific idea is considered, once disconfirming evidence begins to accumulate, at least we know that the notion is untrue. Consider the example of the white swans discussed earlier. One could search the world and see only white swans, and arrive at the generalization that "all swans are white." However, the discovery of one black swan has the potential to overturn, or at least result in modifications of, this proposed law of nature. Finding yet another white swan does not prove anything, its discovery simply provides some comfort that the original idea has merit. Whether scientists routinely try to falsify their notions as has been recommended by philosopher of science Karl Popper, and how much contrary evidence it takes for a scientist's mind to change are fascinating issues (Lakatos, 1972).

MYTH 7: SCIENCE IS PROCEDURAL MORE THAN CREATIVE

We accept that no single guaranteed method of science can account for the success of science, but realize that induction, the collection and interpretation of individual facts providing the raw materials for laws and theories, is at the foundation of most scientific endeavors. This awareness suggests a paradox. If induction itself is not a guaranteed method for arriving at conclusions, how do scientists develop useful laws and theories?

Induction makes use of individual facts that are collected, analyzed and examined. Some observers may perceive a pattern in these data and propose a law in response, but there is no logical or procedural method by which the pattern is suggested. With a theory, the issue is much the same. Only the creativity of the individual scientist permits the discovery of laws and the invention of theories. If there truly was a single scientific method, two individuals with the same expertise could review the same facts and likely reach identical conclusions. There is no guarantee of this because the range, nature, and application of creativity is a personal attribute. See Figure 5 for an illustration of the role of creativity in the knowledge generation process.

Unfortunately, many common science teaching orientations and methods serve to work against the creative element in science. The majority of laboratory exercises, for instance, are verification activities. The teacher discusses what is going to happen in the laboratory, the manual provides step-by-step directions and the student is expected to arrive at a particular answer. Not only is this approach the antithesis of the way in which science actually operates, but such a portrayal must seem dry, clinical and uninteresting to many students. In her 1990 book, *They're Not Dumb, They're Different*, Tobias argues that many capable and clever students reject science as a career because they are not given opportunities to see it as an exciting and creative pursuit. The moral in Tobias' thesis is that science may be impoverished when students who feel a need for a creative outlet eliminate it as a potential career because of the way it is taught.

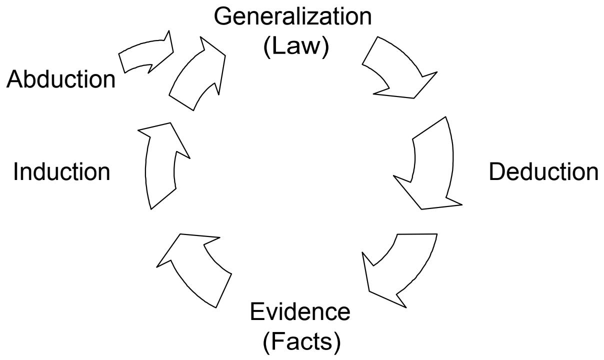

Figure 5. A more accurate illustration of the knowledge generation process in science. Here the creative leap (sometimes called abduction) is shown as a necessary element leading from the evidence to the generalization.

MYTH 8: SCIENCE AND ITS METHODS CAN ANSWER ALL QUESTIONS.

Philosophers of science have found it useful to refer to the work of Karl Popper (1968) and his principle of falsifiability to provide an operational definition of what counts as science. Popper suggested that only those ideas that are potentially falsifiable are scientific ideas.

For instance, the law of gravity states that more massive objects exert a stronger gravitational attraction than do objects with less mass when distance is held constant. This is a scientific law because it could be falsified if newly discovered objects operate differently with respect to gravitational attraction. In contrast, the core idea among creationists is that species were placed on earth fully formed by some supernatural force. Obviously, there is no scientific method by which such a belief could be shown to be false. Since this special creation view is impossible to falsify, it is not scientific and the term "creation science" is an oxymoron. Creation science is a religious belief and as such, does not require that it be falsifiable. Hundreds of years ago thoughtful theologians and scientists carved out their spheres of influence and expertise and have coexisted since with little acrimony. Today, only those who fail to understand the distinction between science and religion confuse the rules, roles, and limitations of these two important worldviews.

It should now be clear that some questions simply must not be asked of scientists. During one of the recent creation science trials for instance, science Nobel laureates were asked to sign a statement about the nature of science to provide some guidance to the court. Seventy-two of these famous scientists responded resoundingly to support such a statement; after all they were experts in the realm of science (Klayman, Slocombe, Lehman & Kaufman, 1986). Later, those interested in citing expert opinion in the abortion debate asked scientists to issue a statement regarding their feelings on this issue. Wisely, few participated. Science cannot answer the moral and ethical questions engendered by the matter of abortion. Of course, scientists as individuals have personal opinions about many issues, but as a group, they must remain silent if those issues are outside the realm of scientific inquiry. Science simply cannot answer moral, ethical, aesthetic, social and metaphysical questions, although it can provide some insights that might be illuminating. For instance, science and resulting technology may be able to clone mammals, but only society can decide whether such cloning is moral and ethical.

MYTH 9: SCIENTISTS ARE PARTICULARLY OBJECTIVE

Scientists are no different in their level of objectivity than are other professionals. They are careful in the analysis of evidence and in the procedures applied to arrive at conclusions. With this admission, it may seem that this myth is valid, but contributions from both the philosophy of science and psychology reveal that complete objectivity is impossible for at least three major reasons.

Many philosophers of science support Popper's (1963) view that science can advance only through a string of what he called conjectures and refutations. In other words, Popper recommends that scientists should propose laws and theories as conjectures and then actively work to disprove or refute those ideas. Popper suggests that the absence of contrary evidence, demonstrated through an active program of refutation, will provide the best support available. It may seem like a strange way of thinking about verification, but the absence of disproof is considered support. There is one major problem with the idea of conjecture and refutation. Popper seems to have proposed it as a recommendation for scientists, not as a description of what scientists do. From a philosophical perspective the idea is sound, but there are no indications that scientists actively practice programs to search for disconfirming evidence.

Another aspect of the inability of scientists to be objective is found in theory-laden observation, a psychological notion (Hodson, 1986). Scientists, like all observers, hold myriad preconceptions and biases about the way the world operates. These notions, held in the subconscious, affect the ability of everyone to make observations. It is impossible to collect and interpret facts without any bias. There have been countless cases in the history of science in which scientists have failed to include particular observations in their final reports. This occurs, not because of fraud or deceit, but because of the prior knowledge possessed by the individual. Certain facts either were not seen at all or were deemed unimportant based on the scientists' prior expectations. In earlier discussions of induction, we postulated that two individuals reviewing the same data would not be expected to reach the same conclusions. Not only does individual creativity play a role, but the issue of personal theory-laden observation further complicates the situation.

This lesson has clear implications for science teaching. Teachers typically provide learning experiences for students without considering their prior knowledge. In the laboratory, for instance, students are asked to perform activities, make observations and then form conclusions. There is an expectation that the conclusions formed will be both self-evident and uniform. In other words, teachers anticipate that the data will lead all pupils to the same conclusion. This could only happen if each student had exactly the same prior conceptions and made and evaluated observations using identical schemes. The does not happen in science nor does it occur in the science classroom.

Related to the issue of theory-based observations is the allegiance to the paradigm. Thomas Kuhn (1970), in his groundbreaking analysis of the history of science, suggested that scientists work within a research tradition called a paradigm. This research tradition, shared by those working in a given discipline, provides clues to the questions worth investigating, dictates what evidence is admissible and prescribes the tests and techniques that are reasonable. Although the paradigm provides direction to the research it may also stifle or limit investigation. Anything that confines the research endeavor necessarily limits objectivity. While there is no conscious desire on the part of scientists to limit discussion, it is likely that some new ideas in science are rejected because of the paradigm issue. When research reports are submitted for publication, other members of the discipline review them. Ideas from outside the paradigm are liable to be eliminated from consideration as crackpot or poor science and thus will not appear in print.

Examples of scientific ideas that were originally rejected because they fell outside the accepted paradigm include the sun-centered solar system, warm-bloodedness in dinosaurs, the germ theory of disease, and continental drift. When the idea of moving continents was first proposed early in this century by Alfred Wegener it was vigorously rejected. Scientists were simply not ready to embrace a notion so contrary to the traditional teachings of their discipline. Continental drift was finally accepted in the 1960's with the proposal of a mechanism or theory to explain how continental plates move (Hallam, 1975 and Mendard, 1986). This fundamental change in the earth sciences, called a revolution by Kuhn, might have occurred decades earlier had it not been for the strength of the prevailing paradigm.

It would be misleading to conclude a discussion of scientific paradigms on a negative note. Although the examples provided do show the contrary aspects associated with paradigm-fixity, Kuhn would likely argue that the blinders created by allegiance to the paradigm help keep scientists on track. His review of the history of science demonstrates that paradigms are responsible for far more successes in science than delays.

MYTH 10: EXPERIMENTS ARE THE PRINCIPAL ROUTE TO SCIENTIFIC KNOWLEDGE

Throughout their school science careers, students are encouraged to associate science with experimentation. Virtually all hands-on experiences that students have in science class are called experiments even if they would more accurately be labeled as technical procedures, explorations or activities. True experiments involve carefully orchestrated procedures accompanied by control and test groups. Usually experiments have as a primary goal the establishment of a cause and effect relationship. Of course, true experimentation is a useful tool in science, but is not the sole route to knowledge.

Many noteworthy scientists have used non-experimental techniques to advance knowledge. In fact, in a number of science disciplines, true experimentation is not possible because of the inability to control variables. Many fundamental discoveries in astronomy are based on extensive observations rather than experiments. Copernicus and Kepler changed our view of the solar system using observational evidence derived from lengthy and detailed observations frequently contributed by other scientists, but neither performed experiments.

Charles Darwin's investigatory regime was frequently more similar to qualitative techniques used in the social sciences than the experimental techniques associated with the natural sciences. For his most revolutionary discoveries, Darwin recorded his extensive observations in notebooks annotated by speculations and thoughts about those observations. Although Darwin supported the inductive method proposed by Bacon, he was aware that observation without speculation or prior understanding was both ineffective and impossible. In fact he stated this view clearly by saying, "I could not help making hypotheses about everything I saw." (Darwin, 1958). The techniques advanced by Darwin have been widely used by scientists such as Goodall and Fossey in their primate studies. Scientific knowledge is gained in a variety of ways including observation, analysis, speculation, library investigation *and* experimentation.

MYTH 11: SCIENTIFIC CONCLUSIONS ARE REVIEWED FOR ACCURACY

When preparing school laboratory reports, students are frequently told to present their methods clearly so that others could repeat the investigation. The conclusion that students will likely to draw from this requirement is that professional scientists are also constantly reviewing each other's experiments to check up on each other. Unfortunately, while such a check and balance system would be useful, the number of findings from one laboratory checked by others is small. In reality, most scientists are simply too busy and research funds too limited for this type of review.

It is interesting to note that when scientific experiments are repeated it is usually because a scientific conclusion attacks the prevailing paradigm. In the recent case of cold fusion, scientists worldwide dropped what they were doing to try to repeat the findings provided by Fleishman and Pons. In fairness, these two scientists not only assailed the conventional wisdom but presented their results in a press conference rather than in a peer-reviewed journal. Therefore, the community of scientists had two reasons to be suspicious. One can infer a measure of the disdain exhibited by the scientific community toward cold fusion and its "discoverers" in the titles of several new books on the subject. *Bad Science: The Short Life and Weird Times of Cold Fusion* (Taubes, 1993) and *Cold Fusion: The Scientific Fiasco of the Century* (Huizenga, 1992) both tell the tale of what happens when a new idea is too far outside scientific norms – at least as far as those norms are presently perceived. The fact that cold fusion did not exist likely vindicated those who quickly attacked it, but the more interesting lesson is that is was attacked because the idea was so distant from the expectation on the part of the scientific community.

The result of the lack of oversight has recently put science itself under suspicion. The pressures of achieving tenure, accruing honors, and gaining funds do result in instances of outright scientific fraud, but fortunately such cases are quite rare. However, even without fraud, the enormous amount of original scientific research published, and the pressure to produce new information rather than reproduce others' work dramatically increases the possibility that errors will go unnoticed.

An interesting corollary to this myth is that scientists rarely report valid, but negative results. While this is understandable given the space limitations in scientific journals, the failure to report what did *not* work is a problem. Only when those working in a particular scientific discipline have access to all information regarding a phenomenon can the discipline progress most effectively.

MYTH 12: ACCEPTANCE OF NEW SCIENTIFIC KNOWLEDGE IS STRAIGHTFORWARD

This misconception addresses the belief that when a more accurate interpretation for the evidence is produced the scientific community will immediately accept it. Nothing could be farther from the truth as we have seen in at least one previous myth. A new idea that is not too far from the expectations of scientists working in a particular field would probably gain entry into scientific journals without much trouble — particularly if it comes from someone working in that field. However, if the idea is a significant breakthrough or revolution in Kuhn's use of the term, particularly if it is counterintuitive or comes from outside the discipline, its acceptance is by no means quick and easy.

The lesson to be learned from this myth, is that science is at its heart a human activity. Humans are the producers of new knowledge and also the arbiters of what counts as new knowledge. While nothing like a vote takes place when a new idea is proposed, the peer review system acts as a gatekeeper to new ideas. Those notions that cannot find a place in the journals will never have a chance to be accepted or denied. Even those new visions of reality that do make it into the journals still have to pass what might best be called the "conference test" if they are to be accepted. Discrepant notions are the talk of professional conferences where they are debated both in the meeting halls but also during dinner and over drinks. As an example, consider the current debate about the origin of modern humans. One view suggests that modern humans arose in various places around the world from ancestral stock while a competing story places the origin of modern humans squarely in Africa from which they migrated to displace the more primitive human forms living elsewhere. The story is told well in a wonderful book, *The Neandertal Enigma* . In this book, Shreeve (1995) discusses the evidence, the personalities and the politics that have directed the conversation about which view should prevail. The final result in the case of human origins is still unsettled, but in many cases, the acceptance of a new scientific idea might be as much a matter of the dynamics of the personalities involved as the strength of the arguments.

MYTH 13: SCIENCE MODELS REPRESENT REALITY

This may be one myth that is shared by both scientists and laypersons alike and is related to the distinction between the philosophical views of realism and instrumentalism. Realism is a position that what science produces not only works and permits the production of accurate predictions but really does represent and/or describe the actual situation in nature as known by some omniscient entity. Of course, one of the central limitations of science is that the "true" nature of reality can never be known because there is no omniscient entity to ask. Science was invented, at least in part, to answer questions about the natural world and get as close to "the truth" as possible, but no bell rings or light blinks to tell scientists that they have found the truth. Another philosophical precept is that as long as the scientific ideas function properly and are consonant with all of the evidence it does not matter whether they correspond with reality or not. The ideas are useful and descriptive and that should be the end of it.

With this distinction between realism and instrumentalism in mind we can now turn to the idea of a scientific model. Although no survey has ever been taken on this issue, it seems logical that scientists do believe that they are not just producing useful ideas but that their ideas and descriptions correspond to a reality external to the scientists themselves. Certainly the average person believes this to be true. It is doubtful that anyone seriously questions the model suggested by the kinetic molecular theory of matter revealing atoms and molecules as tiny discrete balls with elastic collisions. This model explains a range of phenomena. Never mind that no one has ever seen these tiny balls or witnessed their impacts, but the model works; it permits both predictions and explanations and therefore must be true. A realist would say that it is true while an instrumentalist would say it does not matter as long as there is something to be gained from keeping the idea in mind.

The story may be apocryphal, but it is commonly repeated among science educators that when students were once asked what color atoms were, their answer was closely linked to the textbook in use by those students. If the book illustrated atoms as blue, then blue was the color students would assign to atoms when asked. It would probably serve us well to think of models as "useful fictions," but it is doubtful that more than a few keep this warning in mind. After all, what caused Galileo trouble was not that he adopted and supported the sun-centered universe, but that he taught it as the truth in an age when the church felt it had authority over what was considered the truth.

MYTH 14: SCIENCE AND TECHNOLOGY ARE IDENTICAL

A common misconception is the idea that science and technology are the same. In fact, many believe that television, rockets, computers and even refrigerators are science, but one of the hallmarks of science is that it is not necessarily practical while refrigerators certainly are. The pursuit of knowledge for the sake of knowledge alone is called pure science while its exploitation in the production of a commercial product is applied science or technology.

Today, most investigators are working on problems that are at least in part directed from outside their laboratories. Scientists typically blend the quest of pure science in order to solve a technology challenge. In many ways the distinction between pure and applied science is not crucial, but it is interesting to explore what motivates scientists to work on their problems. Few scientists have the luxury to pursue any goal they choose since most scientific work is funded by organizations with an agenda. This funding relationship is not necessarily damaging, but the freedom experienced by the pure scientists of the Victorian age is long gone.

MYTH 15: SCIENCE IS A SOLITARY PURSUIT

Most would likely accept the premise that science builds on prior work, but that essentially great scientific discoveries are made by great scientists. Even the Nobel prizes recognize the achievements of individual scientists rather than research teams. Therefore, science must be a solitary and individual pursuit. Sociologists of science who study scientists at work have shown that only rarely does a scientific idea arise in the mind of a lone individual which is then validated by that individual alone and accepted by the scientific community. The process is much more like a negotiation than the revelation of truth. Scientists work in research teams within a community of like-minded investigators. Many problems in science are simply too complex for a sole individual to pursue alone due to constraints of time, intellectual capital and financing.

CONCLUSIONS

The message from the Science and Engineering Indicators Study (National Science Board, 1996) discussed in the first chapter, and from an evaluation of the myths of science presented here is simple. We must rethink the goals for science instruction. Both students and those who teach science must focus on the nature of science itself rather than just its facts and principles. School science must give students an opportunity to experience science and its processes, free of the legends, misconceptions and idealizations inherent in the myths about the nature of the scientific enterprise. There must be increased opportunity for both beginning and experienced teachers to learn about and apply the real rules of the game of science accompanied by careful review of textbooks to remove the "creeping fox terriers" that have helped provide an inaccurate view of science and its nature. Only by clearing away the mist of half-truths and revealing science in its full light, with knowledge of both its strengths and limitations, will all learners appreciate the true pageant of science and be able to judge fairly its processes and products.

NOTE

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