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PRACTICING SCIENCE

The Investigative Approach in College Science Teaching

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Acknowledgments

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Introduction

Practicing Science: The Investigative Approach in College Science Teaching describes how the skills and processes of investigative learning—inquiry—can be developed and nurtured in the college science classroom. To build this collection, reviewers chose articles from the *Journal of College Science Teaching* that show how college faculty have modified their classes and labs to provide more opportunities to develop inquiry skills. The selected articles illustrate how inquiry contributes to scientific literacy and why it should be a part of all college students' experiences.

The abilities of inquiry to which the *National Science Education Standards* (NRC 1996) refer need little elaboration for college science teachers, who most likely have designed and conducted their own scientific investigations. The Standards use the term to mean (a) a set of abilities and understandings and (b) a set of instructional strategies. Inquiry abilities include identifying researchable questions, designing and conducting scientific investigations, and using logic and evidence to support claims. Inquiry instructional strategies include providing experiences that require students to pose and respond to authentic questions that demand interpretation of evidence and problem solving.

The value of inquiry is described by Lawson in his article "What Should Students Learn about the Nature of Science and How Should We Teach It?" Lawson discusses, in the context of contemporary learning theory, an instructional approach that promotes sound scientific reasoning. His conclusions support inquiry as a means of developing thinking skills and learning about the nature of science.

In "A Science-in-the-Making Course for Nonscience Majors," Tolman describes how her nonmajors pose questions, analyze data, and generally carry out nontraditional activities as they engage in a series of projects designed to give them firsthand experiences with scientific inquiry.

Other articles in this book describe different degrees to which professors have infused inquiry into their courses. One approach is to substitute an inquiry investigation for part or all of an existing lab program. Glasson and McKenzie, in "Investigative Learning in Undergraduate Freshman Biology Laboratories," describe a lab approach whereby students are asked to collaboratively design a series of short-term experiments. Students, with help from teaching assistants, create hypotheses, test their ideas, and propose explanations.

As outlined in "Use of an Investigative Semester-Length Laboratory Project in an Introductory Microbiology Course," Stukus and Lennox require groups of students to conduct a culminating investigation to isolate a randomly selected microorganism. Students conduct library research, formulate their own isolation procedures, and present their results in a final paper. The professors take time at the beginning of the semester to build the student skills required for the investigation that follows. In this approach, lab experiences early in the semester lay the groundwork for those that follow.

Crandall, in "Old Wine into New Bottles: How Traditional Lab Exercises Can Be Converted into Investigative Ones," discusses his experiences with converting traditional labs into investigative ones. He too takes a developmental approach that begins with a discussion early in the semester that weaves together content and experimental design. Crandall follows this discussion with a guided investigation designed to orient students to data collection procedures and interpretation skills. Students then begin to design their own experiments.

Some professors, like Weld, Rogers, and Heard, have their students conduct semester-length laboratory investigations. As they discuss in "Semester-Length Field Investigations in Undergraduate Animal Behavior and Ecology Courses," student teams spend twenty-five to forty hours in the field conducting authentic research that requires them to create hypotheses, make predictions, and design and carry out their own investigations.

Similarly, Harker's students, as described in "Full Application of the Scientific Method in an Undergraduate Teaching Laboratory," select a topic in the beginning of the semester and pursue it in small groups with little teacher intervention. Each group is entirely responsible for its own project and often meets outside of scheduled lab time.

Tichenor, as outlined in "Student-Designed Physiology Laboratories," takes a different approach. She has students work collaboratively during the semester to develop inquiry-based labs that are performed later in the semester by other students in the class. Her incremental, phased approach prepares students

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to design and carry out their own lab exercises. Students evaluate each other's experiments for content and design flaws.

Students in Duch's physics course, as described in "Problem-Based Learning in Physics," learn to see the world from a different point of view. Throughout the semester, they take the role of, for example, a health care worker or an accident investigator to engage in real world problem solving. Like the other contributors to this book, Duch uses field trips, research projects, and cooperative problem solving experiences to challenge students' inquiry skills.

A larger-scale approach to inquiry teaching and learning is illustrated when entire courses are completely revised to encourage more student inquiry. In "A Multidimensional Approach to Teaching Biology," Dimaculangan, Mitchell, Rogers, Schmidt, Chism, and Johnson describe three courses in which students build knowledge and skills throughout the semester as they move from mini-investigations to independent projects.

In summary, the professors featured in this compendium have revised their labs—and, in some cases, their entire courses—so their students have multiple opportunities to develop the abilities and understandings of inquiry. They supplement the traditional lecture with instructional strategies shown to be more effective in meeting inquiry goals. Their successful efforts serve as examples for those who wish to do the same.

Reference

National Research Council (NRC). 1996. *The National Science Education Standards.* Washington DC: National Academy Press.

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What Should Students Learn About the Nature of Science and How Should We Teach It?

Applying the "If-And-Then-Therefore" Pattern to Develop Students' Theoretical Reasoning Abilities in Science

Anton E. Lawson

This article attempts to: 1) explicate the basic pattern of scientific reasoning, 2) show how the pattern has been used to answer a wide range of scientific questions, and 3) argue that sequencing instruction that focuses on that reasoning pattern first in observable contexts and then in non-observable contexts helps students better understand the nature of science and use scientific reasoning in and beyond the science classroom.

Teaching in ways that help students understand the nature of science and how to use scientific reasoning patterns have long been central goals of science education (American Association for the Advancement of Science [AAAS] 1928, 1989, 1990; Educational Policies Commission 1961, 1966; National Science Foundation 1996; National Research Council 1995; National Society for the Study of Education 1960).

However, in spite of a general and long-term philosophical commitment to these goals, the vast majority of research forces the conclusion that the goals have been largely unfulfilled (Lederman 1992; MacKay 1971; National Assessment of Educational Progress 1988; Ryan and Aikenhead 1992).

Part of the problem can be attributed to a justifiable confusion about just what the nature of science is and just what constitutes effective patterns of scientific reasoning. This problem was stated nicely some time ago by the Nobel Prize winning physicist Richard Feynman in an address at the 1966 annual convention of the National Science Teachers Association (Feynman 1966).

In response to the question, What is science?, Feynman was reminded of the following poem: "A centipede was quite happy until a toad in fun said, Pray, which leg comes after which? This raised his doubts to such a pitch, He fell distracted in a ditch."

Feynman went on to remark, "All my life I have been doing science and known what it was, but what I have come to tell you—which foot comes after which—I am unable to do, and furthermore, I am worried by the analogy with the poem, that when I go home, I will no longer be able to do any research."

In spite of Feynman's reservations about how to describe the nature of science, the purpose of this article is to: 1) explicate the central pattern of scientific reasoning, 2) show that the pattern has been applied by scientists to help answer a wide range of scientific questions, and 3) argue that sequencing instruction that focuses on that reasoning pattern first in observable and familiar contexts and then in non-observable and unfamiliar contexts will help students not only better understand what science is, but also help them successfully apply scientific reasoning patterns in and beyond the science classroom.

How Do People Learn?

Take a few minutes to try the task presented in **Figure 1**. You will need a mirror. Once you have a mirror, place the figure down in front of it so that you can look into the mirror at the reflected figure. Read and follow

Anton E. Lawson is a professor in the department of biology, Arizona State University, Tempe, AZ 85287-1501; e-mail: anton.lawson@asu.edu.

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Figure 1. How do people learn? Place this figure in front of a mirror. Read and follow its reflected directions. No fair looking directly at your hand.

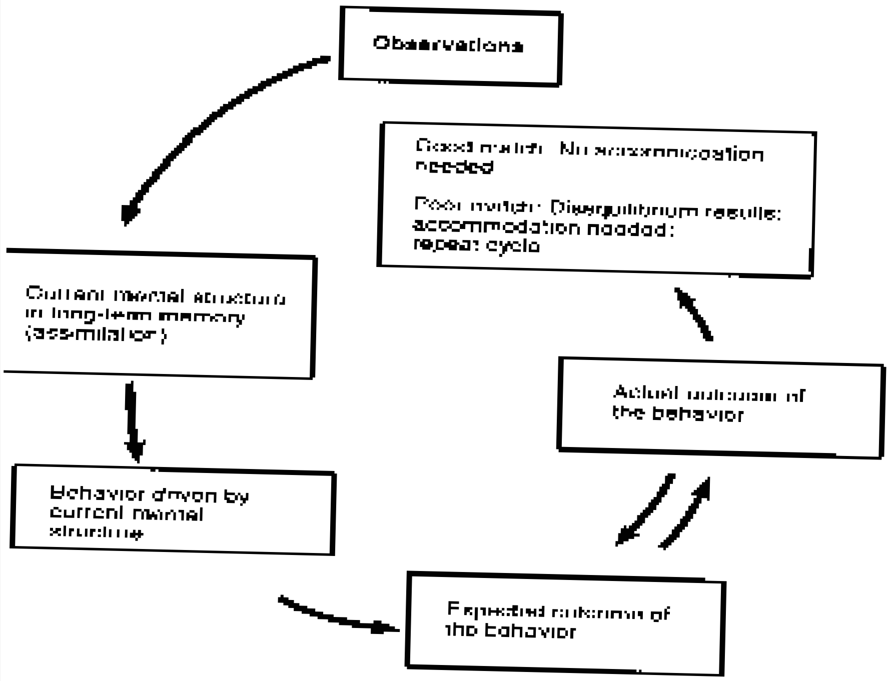
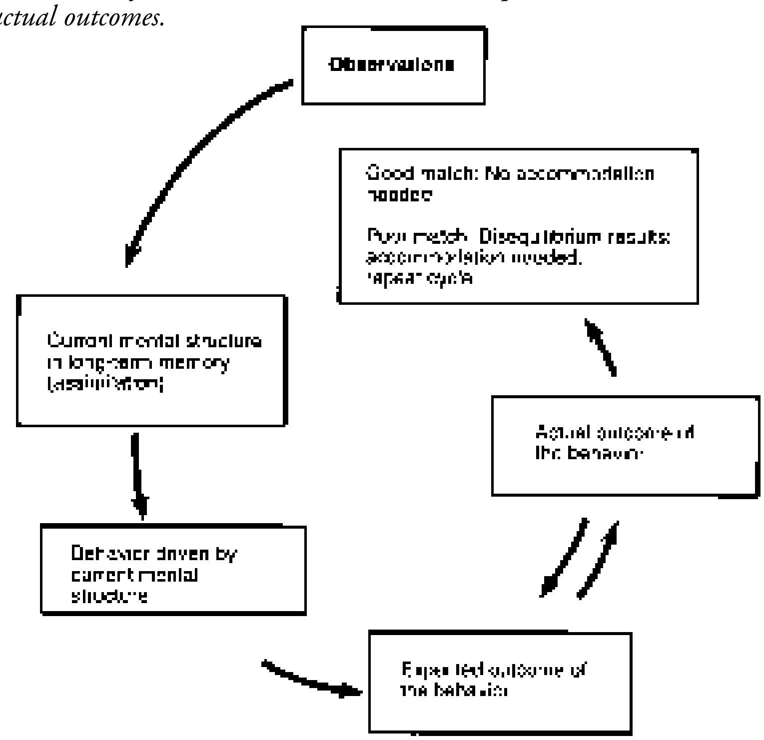


Figure 2. The basic learning pattern begins with assimilation. Disequilibrium and the need for accommodation results when expected outcomes do not match actual outcomes.



the figure's reflected directions. Look only in the mirror—no fair peeking directly at your hand. When finished, read on.

How did you do? If you are like most people, the task proved rather difficult and frustrating. Of course, this should come as no surprise. After all, you have spent a lifetime writing and drawing without a mirror. So what does this little mirror-drawing task tell us about how people learn and about the nature of science?

I think it reveals the basic learning pattern depicted in **Figure 2** and described as follows: First, the reflected images are assimilated by specific "mental structures" that are currently part of your long-term memory. These mental structures then drive behavior that, in the past, has been linked to consequences (i.e., actual outcomes). Thus, when the structures are used to drive behavior in the present context, the behavior is linked to an expected outcome.

All is well if the behavior is successful—that is, if its actual outcome matches the expected outcome. However, if unsuccessful, that is, if its actual outcome does not match the expected one (e.g., your hand moves to the left and down and you expect to see a line drawn to the left and down, but instead you see one drawn to the left and *up*), contradiction results.

This contradiction then drives a subconscious search for another mental structure and perhaps a closer inspection of the figure until either another structure is found that works (in the sense that it drives successful, noncontradicted behavior), or you become so frustrated that you quit. In the latter case, your mental structures will not undergo the necessary accommodation (cf. Karplus, Lawson, Wollman, Appel, Bernoff, Howe, Rusch, and Sullivan 1977; Piaget 1971; Lawson 1994). In other words, you won't learn to draw successfully in a mirror.

CAN THIS LEARNING PATTERN BE USED TO ANSWER "SCIENTIFIC" QUESTIONS?

The top row of **Figure 3** shows

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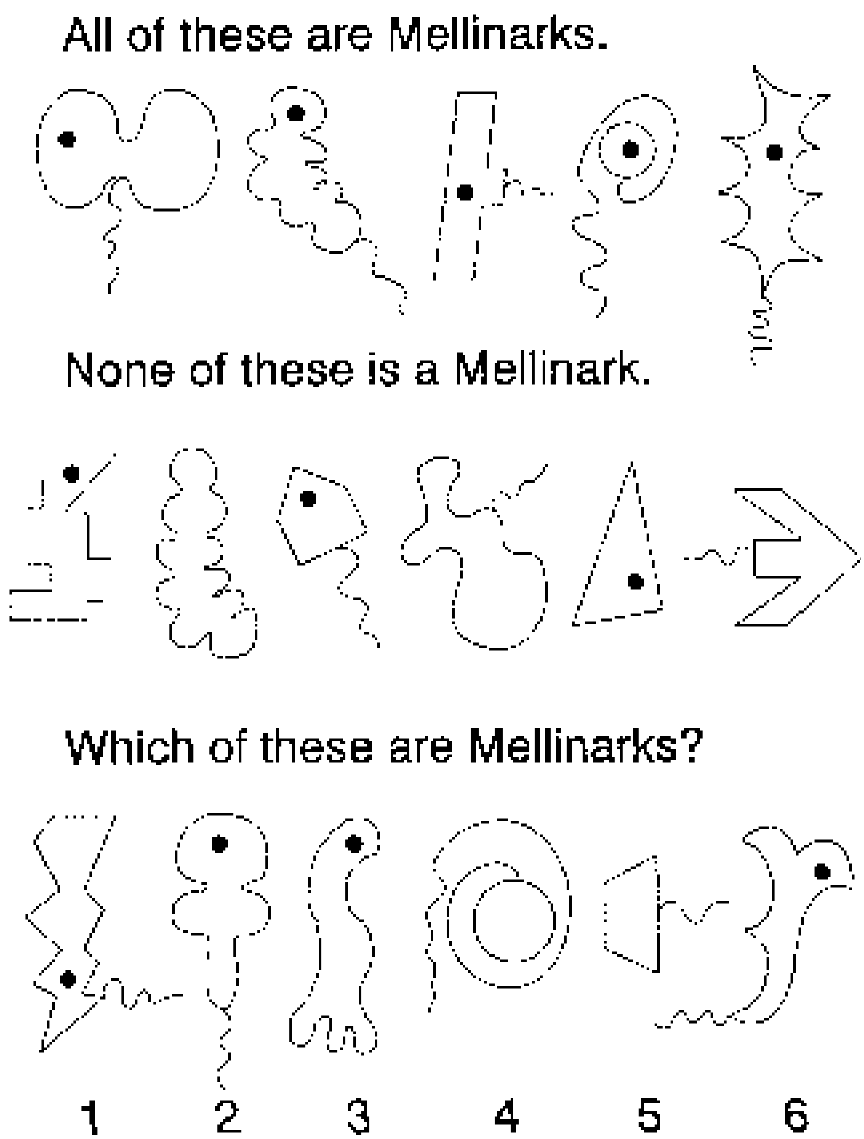
"creatures" called Mellinarks. Notice that none of the creatures in the second row are Mellinarks. Your job in this task is to figure out which creatures in the third row are Mellinarks. Take a few minutes to see what you come up with.

Did you conclude that creatures one, two, and six of row three are Mellinarks? If so, how did you arrive at that conclusion? This question is tough because it is difficult to reflect on one's reasoning. Nevertheless, allow me to present a strategy that previous research indicates successful students use (Lawson 1993). See if it comes close to what you did. First, we glance at the Mellinarks in the first row and see that they all contain one large dot. Could one large dot be the key feature of Mellinarks? We can test this idea as follows:

*If...*Mellinarks are creatures with one large dot (proposed key feature),
*and...*we look at the non-Mellinarks in row two (behavioral test),
*then...*none of them should contain a large dot (expected outcome).
*But...*creatures one, two, and four in row two each contain a large dot (actual outcome).
*Therefore...*Mellinarks are not creatures defined solely by the presence of one large dot. We need to generate and test another idea (conclusion).

Recycling this reasoning pattern eventually prompts the reasoner to generate, test, and support the idea that Mellinarks are defined by the presence of one large dot, a curly tail, and shading. Hence, creatures one, two, and six in row three are Mellinarks. Notice in **Figure 4** that this if-and-then-therefore pattern is the same pattern used in the mirror task. The primary difference is that the mirror task was nonverbal and sensory-motor, while the Mellinark task involves feature detection and linguistically-mediated arguments to arrive at a successful (i.e., noncontradicted) classification scheme of Mellinarks and non-Mellinarks.

Figure 3. *Which creatures in row three are Mellinarks? What reasoning pattern(s) did you use to find out?*



Can the Same Reasoning Pattern be Used in Causal Contexts?

Successfully identifying features and variables, and using them to form classes and subclasses of objects, is an important component of science. But there is much more to science than description and classification. Scientists seek to understand nature in terms of causes and effects. Can the if-and-then-therefore pattern also be used in causal contexts?

Consider the case of silver salmon. Silver salmon are found in the headwaters of freshwater streams in the Pacific Northwest. Young salmon swim downstream to the Pacific Ocean, where they grow and mature sexually. They then return to the freshwater streams and swim upstream to ultimately lay their eggs in the headwaters before dying. By tagging young salmon, biologists discovered that mature salmon actually migrate to

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precisely the same headwaters in which they hatched some years earlier. This discovery raised a very interesting question: How do returning salmon locate their homestreams?

A number of alternative hypotheses can be proposed. For instance, humans often navigate by sight. Perhaps salmon do as well. Salmon may remember certain objects, such as large rocks they saw when swimming downstream on their way to the ocean. They then see these and use them to navigate on their return journey.

Studies of migratory animals also suggest hypotheses. For example, biologists have found that migratory eels are enormously sensitive to dissolved minerals. Perhaps salmon are as well. In other words, perhaps salmon use their noses to detect smells specific to their homestreams.

Thus, the use of analogies (i.e., borrowing ideas from similar contexts—sometimes referred to as analogical reasoning) gives us two alternative hypotheses: Salmon use sight to find their homestream. Or salmon smell substances specific to their homestream, which they follow upstream.

The next task is to test the alternatives. During the 1960s, American biologist A.D. Hasler conducted an experiment to test the sight hypothesis using the following reasoning:

*If...*silver salmon locate their homestream by sight (sight hypothesis),

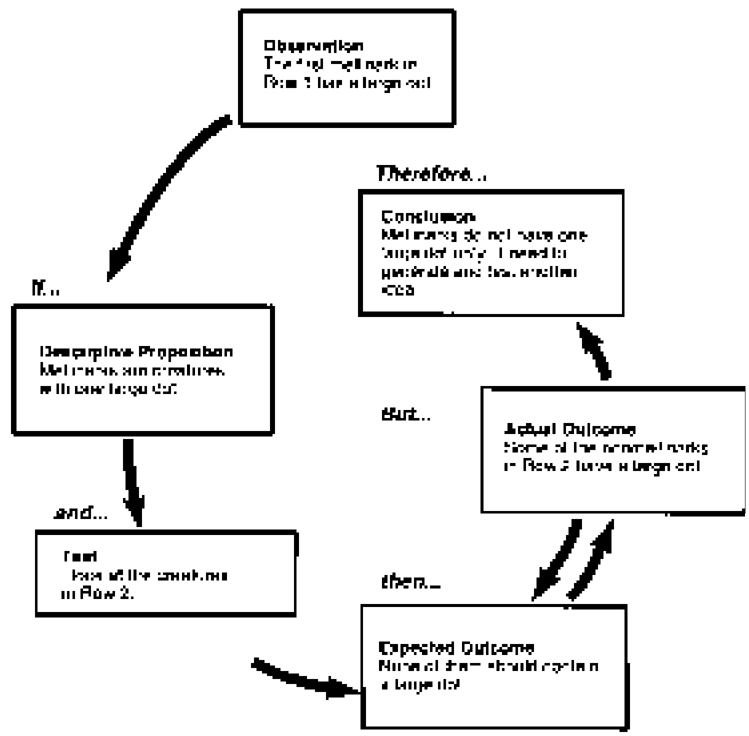
*and...*returning salmon are captured from two homestreams (see **Figure 5**). Some fish from each stream are then blindfolded, while others are not. All of the fish are then released below the junction where the streams join, and the returning fish are then recaptured in traps above the junction as they swim back up the streams (test conditions),

*then...*the blindfolded salmon should be recaptured in their homestreams at a significantly lower rate than the non-blindfolded salmon (expected result).

*But...*the blindfolded salmon were recaptured in their homestreams at the same rate as the non-blindfolded salmon (actual result).

*Therefore...*the sight hypothesis is contradicted (conclusion).

Figure 4. The basic learning pattern applied to the Mellinark task.



This example shows that the if-and-then-therefore reasoning pattern can indeed be used to test causal hypotheses. Importantly, in spite of the similarity in pattern, students as young as seven years old can successfully use if-and-then-therefore reasoning to solve Mellinark-type tasks—that is to solve descriptive/classification tasks (Lawson 1993). But they do not successfully apply it to test hypotheses in causal contexts until much later—around age 12 (Inhelder and Piaget 1958). In fact some college-age students still exhibit difficulties in its use in causal contexts—a point that will be returned to later (Dawson and Rowell 1986; Lawson 1992; Walker 1979).

Before leaving the salmon example, one further point should be made. (By the way, Hasler did eventually find support for the smell hypothesis as fish with their noses plugged were not as good at finding their homestreams as those that could smell.) Consider the relationship between Hasler's sight and smell hypotheses and the independent variables manipulated in his experiments. In effect, the possible causes—the hypotheses—were the manipulated variables, i.e., the ability-to-see variable and the ability-to-smell variable.

In other words, to experimentally test these types of causal hypotheses, you manipulate the hypothesized cause (i.e., you blindfold the fish, you plug the fishes' noses), and you wait to see if the outcome is affected (i.e., the fish stop returning to their homestream). If the outcome is affected, then the hypothesis is supported. If not, the hypothesis is contradicted; something else is probably causing the effect.

IS IF-AND-THEN-THEREFORE REASONING ALSO USED IN CORRELATIONAL CONTEXTS?

But one can not always manipulate hypothesized causes. Sometimes corre-

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lational evidence is all that one can obtain. Can if-and-then-therefore reasoning also be used to test hypotheses with correlational data? Suppose one wants to test the hypothesis that silicone-gel-filled breast implants cause connective-tissue disease in women. Clearly experimentation is unethical and out of the question. Nevertheless, consider the following argument:

*If...*silicone-gel-filled breast implants cause connective-tissue disease (breast-implants-cause-disease hypothesis)

*and...*the incidence of connective tissue disease in women with silicone-gel implants is compared with disease incidence in women without implants (test conditions)

*then...*the disease incidence should be significantly higher for the women with implants than for those without implants (expected results).

*But...*the disease incidence is not significantly higher for women with implants. For example, a 1994 study reported in *The New England Journal of Medicine* found a 0.06% incidence of connective-tissue disease among women with implants. Disease incidence among an age-matched group of women without implants from the same area for the same time period was also 0.06% (actual results).

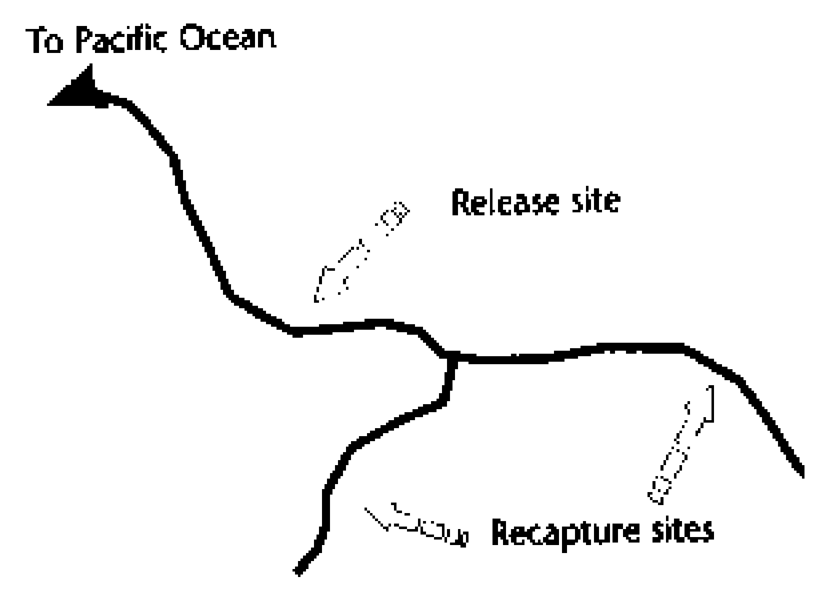
*Therefore...*the breast-implants-cause-connective-tissue-disease hypothesis is contradicted (conclusion).

Notice that the preceding argument and correlational evidence do indeed test the causal hypothesis, though not as convincingly as a controlled experiment might. Can if-and-then-therefore reasoning also be used to test scientific theories that claim the existence of unseen entities?

How Are Theories That Claim the Existence of Unseen Entities Tested?

The ancient Greeks discovered that a candle placed under an inverted jar burns for a short time and then goes out. By the 1700s most scientists explained this by imagining that materials, such as candles, consist of a base plus something called phlogiston. According to phlogiston theory, when a candle burns, its unseen phlogiston is released into the air and its base is left behind as ashes. Thus, a flame under the inverted jar goes out because the jar's air becomes saturated with phlogiston. When the air is full of phlogiston, burning stops and the flame goes out.

Figure 5. *Release and recapture sites used in testing the sight and smell hypotheses.*



Phlogiston theory makes sense and it seems to agree with the observations. Certainly one can "observe" flames going from candles into air. But phlogiston theory was not entirely free of difficulties as can be seen in the following argument:

*If...*phlogiston is an unseen material (which like other materials has weight) that escapes from metals during burning (phlogiston theory)

*and...*a metal is weighed before and after it burns and turns into ashes (test condition),

*then...*the ashes should weigh less than the original metal (expected result). The ashes should weigh less because part of the initial material (the phlogiston) has escaped into the air (theoretical rationale).

*But...*the ashes weigh more, not less, than the original metal (observed result).

*Therefore...*phlogiston theory is contradicted (conclusion).

What do you suppose the phlogistonists did with this contradictory result? Instead of rejecting the theory, they simply imagined that phlogiston has *negative* weight! Consequently, they argued that adding phlogiston to something should decrease its weight, and removing phlogiston should increase its weight.

The idea of negative weight may seem much too strange to take seriously. But it does make some sense. After all, phlogistonists argued, fire seeks its "natural" place above air, thus, fire (phlogiston) should have negative weight. If you still think this idea of negative weight is too strange, consider the "attractive" *and* "repulsive" forces of common magnets, forces that were well known at the time. If magnets can attract *and* repel things, why can't phlogiston have negative weight? Small wonder that phlogiston theory was well accepted by eighteenth-century chemists.

Regardless of the fact that contradictory results do not necessarily cause people to abandon theories, the phlogiston example does at least

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demonstrate that if-and-then-therefore reasoning can be used to put theories about unseen entities to the test. Let's consider one more example.

HOW DO NERVE IMPULSES PASS BETWEEN CELLS?

A microscopic look at the place where one neuron contacts another, or where a neuron contacts a muscle cell, reveals that the cells come very close to one another, but they do not touch. Instead, tiny gaps called synapses exist. In other words, synapses separate neurons from each other and from muscle cells. Thus, another question presents itself: How do nerve impulses travel across synapses?

During the late 1800s and early 1900s, most physiologists suspected that electrical transmission was involved. Diffusing chemicals just seemed too slow to account for the apparent speed of transmission. Nevertheless, in 1921, chemical-transmission theory got a big boost thanks to a most improbable experiment conducted by German physiologist Otto Loewi.

Loewi's experiment involved a frog whose heart he dissected out along with the nerve connecting the heart to the spinal cord. When Loewi electrically stimulated the nerve, the heartbeat slowed. So apparently the nerve helps regulate heart rate. Loewi then thought of a way to use the nerve and heart to test chemical-transmission theory. In fact, he thought of the test in a dream! He was so excited by his dream that he awoke and immediately wrote down his plan. But in the morning when he tried to read what he had written, he found it unintelligible. Fortunately, a few nights later, the dream recurred.

This time, taking no chances, Loewi awoke and immediately went to his lab to conduct the test. His reasoning and test went as follows:

*If...*the transmission of impulses between neurons and from neurons to muscle cells involves the flow of molecules across synapses (chemical-transmission theory)

*and...*the frog's nerve (mentioned above) is stimulated several times to slow its heart rate while the heart is bathed in a fluid (test conditions),

*then...*when that fluid is collected and applied to another frog's heart, its heartbeat should also slow (expected result). This result is expected because the imagined molecules produced by the stimulated nerve in the nerve-heart preparation should pass through the synapses separating the neurons and heart muscle cells and collect in the fluid. So when the fluid is applied to the second heart, the molecules in the fluid should produce the same effect, that is slow the second heart (theoretical rationale).

*And...*as expected, Loewi found that the fluid caused the second heart to slow. The fluid had the same effect on several other tissues as well (actual result).

*Therefore...*Loewi's improbable experiment provided convincing support for chemical-transmission theory (conclusion). The unseen diffusing chemical was later identified as acetylcholine.

HOW GOOD ARE COLLEGE STUDENTS AT GENERATING THEORETICAL ARGUMENTS?

College students are fairly proficient at generating if-and-then-therefore arguments in contexts in which the hypothesized causes are observable and relatively familiar (e.g., salmon experiment, breast-implant situation). But doing the same in theoretical contexts that involve unseen entities such as phlogiston or acetylcholine proves much more difficult.

More specifically, following instruction, over 90 percent of the college students in a recent study successfully generated if-and-then-therefore arguments when the proposed causes were familiar and observable. But less than 25 percent did so when they were unfamiliar and unseen (Lawson, Drake, Johnson, Kwon, and Scarpone 1997). Why should this be?

The answer may in part be simply due to lack of familiarity and the fact that the proposed causal agents are no longer observable. But there may be more to it than this. Notice that testing ideas in theoretical contexts also requires an extra step in reasoning. Whereas the previous experimental or correlational tests directly manipulated or varied the hypothesized causes, this is no longer the case in theoretical contexts.

For example, in the phlogiston test, the proposed cause of flames going out was the saturation of air with an unseen substance (phlogiston) and the experiment involved weighing a metal before and after burning. Similarly, in Loewi's experiment, the imagined cause of impulse transmission was the diffusion of unseen molecules across synapses, and the experiment involved the stimulation of frog's nerve while its connected heart was bathed in fluid, and then placing that fluid on a second heart.

In other words, the relationship between the proposed cause and the experimental design is no longer obvious and direct. Consequently, a theoretical rationale (i.e., an explicit statement of the relationship between the imagined cause and the test) needs to be added to the argument.

HOW CAN TEACHERS HELP STUDENTS DEVELOP THEORETICAL REASONING PATTERNS?

As we have seen, learning involves an idea-testing process that follows the if-and-then-therefore pattern. The pattern may be explicitly stated, as was the case for several scientific examples in this paper; or it may operate on a subconscious, nonverbal level, as was the case for the mirror drawing. Moreover, the development of scientific reasoning patterns (i.e., acquisition of learning-to-learn strategies) appears to occur in a sequential stage-like manner in which the if-and-then-therefore pattern is first applied in sensory-motor contexts and only later in descriptive (i.e., categorical) Mellinark-like contexts, and still later in hypothetical contexts. Some people, including scientists, even develop the ability to use the pattern in theoretical contexts.

Importantly, it would seem that development of this sort of theoretical reasoning ability is necessary for under-

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standing the theoretical nature of science. Given that few college students give evidence of theoretical reasoning ability (perhaps less than 25 percent), the key pedagogical question is this: How can we help the other 75 percent develop theoretical reasoning patterns and acquire an accurate understanding of the nature of science?

If intellectual development is truly stage-like, then for "descriptive" students it would appear that we need to immerse them in "hypothetical" contexts and provide lots of opportunities for direct physical experience, for social interaction with others, and for equilibration (cf., Piaget and Inhelder 1969). Once these students develop hypothetical reasoning patterns, we then need to repeat the process in theoretical contexts.

In other words, as teachers we need to: 1) know where our students are in their intellectual development, 2) be aware of the intellectual demands that instructional tasks place on student reasoning abilities, 3) correctly match instructional contexts with student abilities, and 4) sequence contexts in a way that moves from description and classification, to causal hypothesis testing in familiar contexts, to causal hypothesis testing in not-so-familiar contexts, and then to theory testing (where theories are defined as general explanatory systems that postulate the existence of unseen entities and/or processes).

Table 1. Postulates of Kinetic-Molecular Theory Used to Explain the Water Rise.

1. *The universe contains matter, which is composed of tiny particles (atoms and combinations of atoms called molecules) and light, which consists of still smaller particles called photons.*

2. *Atoms/molecules are in constant motion. They strike other atoms/molecules and transfer some or all of their motion (kinetic energy) to these particles.*

3. *An energy source, such as a flame, consists of rapidly moving particles that can transfer some, or all, of their motion to nearby particles through collisions.*

4. *Attractive forces between atoms or molecules can be broken, causing the atoms or molecules to move apart, which in turn can cause collisions and transfers of energy (motion).*

5. *Molecular bonds can form between atoms when they strike one another.*

6. *Temperature is a measure of the amount of motion (average kinetic energy) of the atoms/molecules in a solid, liquid, or gas (i.e., the more motion the greater the temperature).*

7. *Air pressure is a force exerted on a surface due to collisions of air particles (i.e., more particles at higher velocities = greater air pressure).*

WHY DOES WATER RISE IN THE CYLINDER?

Let's see how we can teach a lesson involving use of if-and-then-therefore thinking and unseen theoretical entities to help students develop theoretical reasoning patterns and a more accurate understanding of the nature of science.

Background Information. The lesson begins with a burning candle held upright in a pan of water using a small piece of clay. Shortly after a cylinder is inverted over the burning candle and placed in the water, the candle flame goes out and water rises in the cylinder. These observations raise two major causal questions: Why did the flame go out? And why did the water rise?

The generally accepted answer to the first question is that the flame converted the oxygen in the cylinder to carbon dioxide such that too little oxygen remained to sustain combustion, thus the flame died. The generally accepted answer to the second question is that the flame transfers kinetic energy (motion) to the cylinder's gas molecules. The greater kinetic energy causes the gas to expand, which results in some escaping out the bottom. When the flame goes out, the remaining molecules transfer some of their kinetic energy to the cylinder walls and then to the surrounding air and water.

This transfer causes a loss of average velocity, fewer collisions, and less gas pressure (a partial vacuum). This partial vacuum is then filled by water rising into the cylinder until the air pressure pushing on the outside water surface is equal to the air pressure pushing on the inside surface (Peckham 1993).

This lesson is a particularly good way to reinforce the idea that science is an alternative explanation, generation, and testing enterprise as the initial explanations students often generate to explain why the water rises are experimentally contradicted. Hence, mental disequilibrium results along with the need for accommodation. In other words, their ideas need to be replaced.

A common student explanation centers around the idea that oxygen is "used up," thus a partial vacuum is created, which "sucks" water into the cylinder. Typically, students fail to realize that when oxygen "burns" it combines with carbon producing CO_2 gas of equal volume (hence no partial vacuum is created). Students also often fail to realize that a vacuum cannot "suck" anything. Rather the force causing the water to rise is a push from the relatively greater number of air molecules hitting the water surface outside the cylinder.

Student experiments and discussions provide an opportunity to modify these misconceptions by introducing a more satisfactory explanation of combustion and air pressure. An opportunity also exists to portray science as an intellectually stimulating and challenging way of using theories, in this case kinetic-molecular theory (see **Table 1**) to explain nature.

Starting the Lesson. Start the lesson by pointing out the following

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materials:

- ▲ aluminum pie pans
- ▲ birthday candles
- ▲ matches
- ▲ modeling clay
- ▲ cylinders (open at one end)
- ▲ jars (of various shapes, sizes)
- ▲ beakers and/test tubes/flasks
- ▲ syringes and rubber tubing
- ▲ baking soda
- ▲ ice
- ▲ dry ice
- ▲ balloons
- ▲ pH paper

Have each student select a partner. Tell each pair to pour some water into the pan. Stand a candle in the pan using a small piece of clay for support. Then light the candle and put a cylinder, jar, flask, or beaker over the candle so that it covers the candle and sits in the water. Then observe what happens and repeat the procedure several times varying several independent variables (e.g., the number of candles, amount of water, type of cylinder) to determine their possible effects.

You should also tell students that they will not only be challenged to generate several alternative explanations for what they observe, but they will also be challenged to design experiments to test the alternatives. (Of particular interest is the fact that on a number of past occasions "hypothetical" students—and sometimes teachers—feel that they have completed the lesson when they have identified variables that affect the level of water rise. They don't even realize that their "theoretical" task has just begun!)

Generating Alternative Explanations. Allow the initial exploration to proceed as long as students are making good progress. You may need to stop them after about 30-40 minutes to discuss observations, preliminary questions, and explanations. During the discussion, observations should be listed on the board and you should ask students to state the key causal question(s) raised.

The most obvious causal questions are: Why did the flame go out? And why did the water rise? Alternative explanations that students may generate to answer the second question include:

1) The oxygen is "burned up" creating a partial vacuum. So the water is "sucked" in to replace it.

2) H_2O gas is formed by burning. When the H_2O cools, it changes to liquid filling the cylinder.

3) As the candle burns, it consumes O_2 but produces an equal volume of CO_2. The CO_2 dissolves in the water more easily than the original O_2, producing a partial vacuum. The water is then "sucked" in.

4) The candle produces smoke, which collects in the cylinder and attracts (pulls) the water up.

5) Burning converts O_2 to CO_2, which is a smaller molecule. Thus, it takes up less space, creating a partial vacuum that "sucks" the water up.

6) The candle's heat causes the air around it to expand. After the candle goes out, the air cools, air pressure is reduced, and the water is pushed in by greater air pressure outside. (If no one proposes this explanation you will have to propose it yourself. But make sure that you do not give students the impression that this is the "correct" explanation. Rather, it is simply an idea that a student in another class generated, which should be tested along with the others.)

7) Here is an explanation that I like to add to the students' list: A Wizard named Sparky lives on campus and sucks the water up. (Sparky is the name of our university sports mascot).

Testing the Alternatives. Now that student brainstorming has generated several possible explanations, remind students that this is a science class. Consequently, their next task is to test the alternatives. Also remind them that to test a possible explanation one must conduct experiments with clearly stated expected results (predictions).

You may want to provide an example, or simply challenge students to put their heads together to see what they can come up with. This may be an excellent time for the bell to ring so that they can think up experiments as a homework assignment. If you do decide to offer an example, use the if-and-then-therefore form. For example:

If...explanation 1 is correct, that is if water is "sucked" up because oxygen is consumed creating a partial vacuum (oxygen-consumed explanation)

and...the height that water rises with one, two , three, or more candles (all other things being equal) is measured (test conditions)

then...the height of water rise should be the same regardless of the number of burning candles (expected result). This result is expected presumably because there is only so much oxygen in the cylinder to be burned. So more candles will burn up the available oxygen faster than fewer candles, but they will not burn up more oxygen. Hence, the water level should rise the same. Note that the assumption is made that before they go out, more candles do not consume more oxygen than fewer candles (theoretical rationale).

Now have students conduct their experiments and report results. Results of the example experiment show that the water level is affected by the num-

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ber of candles (the more candles the higher the water level). Therefore the oxygen-consumed explanation has been contradicted. Also the water rises after the candles go out, not while they are burning—another observation that contradicts explanation 1.

Explanation 2, the water-created-by-burning explanation, can be tested by measuring the total volume of water before and after the water has risen inside. If this explanation is correct, the total volume of water should increase considerably.

Explanation 3 claims that the CO_2 dissolves in the water. Students can test this explanation in a couple of ways. One way involves a comparison of the amount of water rise in containers with CO_2-saturated water versus normal water. The explanation leads to the prediction that the water level should rise higher in the cylinder with normal water. One can use dry ice (or sodium bicarbonate and acid) to produce CO_2 gas. Its solubility in water can be tested. The pH of water shaken with CO_2 and the pH of the water below a candle that has just gone out can be compared.

Also, if the explanation is correct, a cylinder filled with gas from the dry ice (presumably CO_2) when inverted and placed in water should cause water to rise, but water doesn't.

Explanation 4, the smoke-attracts-water explanation, can be tested by filling a cylinder with smoke and inverting it in water. If the explanation is correct, the water should rise.

I will leave it to you to figure out a way to test explanation 5, the CO_2-is-a-smaller-molecule explanation.

Explanation 6, the heat-causes-air-expansion explanation, leads to the prediction that bubbles should be seen escaping out the bottom of the cylinder (assuming that the cylinder is quickly placed over the candles while the air is still expanding). It also leads to the prediction that more candles should cause more water to rise—presumably because more candles will heat more air, thus, more will escape, which in turn will be replaced by more water. (Although one candle burning over a longer time period releases as much energy as three candles burning a shorter time, one candle will not raise the cylinder's air temperature as much because energy is dissipated rather quickly.)

Initially students do not take explanation 7, the Sparky-sucks explanation, seriously. So they don't bother to test it. But at my insistence, they soon come up with the idea of conducting the experiment off campus based on the following reasoning:

*If...*the water rises because Sparky sucks it up (Sparky explanation)

*and...*the experiment is conducted off campus (test condition)

*then...*the water should not rise (expected result).

*But...*they surmise that the water does rise off campus (actual result).

*Therefore...*the Sparky explanation can be rejected (conclusion).

I reply to this argument that, since they are Arizona State University students, Sparky travels with them off campus. Consequently, he can still make the water rise. So their experiment does not really contradict the Sparky explanation after all.

Students then propose to have the experiment done by telephoning a non-ASU student and asking him or her to conduct the experiment off campus. Then when the non-ASU student finds that the water still rises, students conclude that the Sparky explanation can be rejected. But Sparky's powers can travel through phone lines, I tell them, so the water should still rise.

At this point most students catch on to the game being played, which essentially amounts to giving Sparky ever-expanding powers. And once Sparky's powers become limitless, the Sparky explanation can no longer be tested. Thus, continued belief in Sparky becomes a matter of faith, not evidence. In other words, Sparky becomes a religious, God-like, entity, not a scientific (i.e., testable) entity. This discussion is important because it clarifies this essential difference between religion and science for many students for the first time.

Introducing and Applying Kinetic-Molecular Theory. After all the alternatives have been tested and the results discussed, you should carefully summarize and clarify the explanation that is most consistent with the evidence. You can also introduce the term air pressure and the major postulates of the kinetic-molecular theory as they pertain to the present phenomenon. You should also discuss the common misconception of "suction" in this context. Kinetic-molecular theory implies that suction (as a force that can suck up water) does not exist (i.e., the water is being pushed into the cylinder by moving particles of air rather than being sucked by some intuitively generated but non-existent force).

To allow students to apply kinetic-molecular theory and the concept of air pressure to a new situation, provide each group a piece of rubber tubing, a syringe, a beaker, and a pan of water. Instruct them to invert the beaker in the pan of water and fill it with water in that position with the mouth of the beaker submerged. Some students will make futile efforts to force water through the tube into the beaker before discovering that they must extract the air through the tube.

As a homework assignment, challenge the students to find a way to insert a peeled, hard-boiled egg into a bottle with an opening that is smaller in diameter than the egg. They must not touch the egg with anything after it has been placed on the opening. After a small amount of water in the bottle has been heated, it is only necessary to place the smaller end of the egg over the opening of the bottle to form a seal. The egg will be forced into the bottle by the greater air pressure outside as the air inside cools. You may also ask students to drink a milk shake with a straw and then challenge them to explain how the milk shake gets into their mouths.

What Does the Candle-Burning Lesson Teach Students About the Nature of Science?

In addition to providing students with experience in using theoretical

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reasoning to generate and test alternative explanations, the candle-burning lesson exemplifies these important characteristics of science:

▲ Science is a human activity that attempts to accurately describe and explain nature by raising and answering descriptive and causal questions. Science consists of methods of description and explanation plus the descriptions and explanations that have been obtained.

▲ Basic to doing science is the generation and test of alternative explanations. Explanations are generated by use of the creative process of abduction (analogical reasoning). The initial generation of several alternatives encourages an unbiased test as one is less likely to be committed to any specific explanation. Tentative explanations are tested by use of an if-and-then-therefore reasoning pattern. A test begins by assuming that the explanation under consideration is true and by imagining some test condition(s) that allows the deduction of one or more expected results (predictions). Data (actual results) are then gathered and compared with the expected result(s). A good match provides support for the explanation, while a poor match contradicts the explanation and may lead to its rejection.

▲ Although inductively derived generalizations and explanations are both tested by use of the if-and-then-therefore reasoning pattern, generalizations and explanations are not the same thing. Generalizations (sometimes called laws) describe nature in terms of identifiable patterns (e.g., more candles make more water rise; the sun rises in the east and sets in the west; salmon spawn in their homestreams), while explanations (both hypotheses and theories) attempt to provide causes for such patterns.

▲ People do science to find out why things happen, to find causes. People want to know the causes of things to satisfy their curiosity—basic research—or so that their new knowledge can be put to practical use—applied research.

▲ Like hypotheses, theories are explanations of nature. But while hypotheses attempt to explain a specific observation, or a group of closely related observations, theories attempt to explain broad classes of related observations, hence tend to be more general, more complex, and more abstract.

▲ Theory testing, like hypothesis testing, involves use of if-and-then-therefore reasoning. But because of the additional complexity, theories can seldom be tested in their entirety. Rather, they most often are tested component by component. Further, because of the additional abstractness, theory testing often requires the inclusion of a theoretical rationale, which links abstract and non-observable (i.e., theoretical) causal agents with observable experimental manipulations (independent variables).

▲ Theory testing may be further complicated when an advocate of a contradicted theory decides to modify, rather than reject, the theory. The modification may involve a change in a basic component, or the addition of new components. Modifications are intended to keep the theory consistent with the evidence. Nevertheless, theories that meet with repeated contradiction are generally replaced, particularly when a reasonable noncontradicted alternative exists.

▲ Although it is common practice to speak as though entities such as oxygen and carbon dioxide have been "discovered" in a manner similar to the way someone discovers a lost treasure, this practice is misleading. Instead, entities such as oxygen and carbon dioxide, like the vital force and phlogiston, can be better understood as conceptual inventions, albeit conceptual inventions that have been so thoroughly tested that their existence is no longer in question.

▲ Because any two hypotheses or theoretical claims may lead deductively to the same expected result, observation of that result can not tell you which hypothesis or theoretical claim is correct. For this reason, supportive evidence can not prove that a hypothesis or theory is correct.

▲ Contradictory evidence can arise because of either an incorrect hypothesis/theory or a faulty test (e.g., one in which not all other variables were held constant). Further, because it is not possible to be certain that all other variables were in fact held constant, contradictory evidence can not prove that a hypothesis or theory is incorrect.

▲ Science and religion are fundamentally different "ways of knowing." Science asks that one generate alternative explanations and then consult nature as a way of testing the alternatives. Scientific knowledge, which must remain somewhat tentative, comes at the end of the process. On the other hand, religion asks that one accept a particular explanation at the outset based on faith. Nature need not be consulted and religious knowledge is considered absolute.

Conclusions and Recommendations

In conclusion, it should be pointed out that the above list of statements about the nature of science represent generalizations, and as such can be learned only superficially from single-shot instruction, such as the candle-burning lab, no matter how engaging it may be. Both developmental theory and experience argue that learning about the nature of science and developing theoretical reasoning abilities are long-term propositions, which, like learning to draw in a mirror, require repeated attempts in a variety of contexts.

Indeed, the problem is compounded by the fact that students often encounter misleading statements about the nature of science, not only from television reports and newspaper articles claiming that science has proved, or disproved, such and such, but even from science textbook au-

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thors and teachers. Most likely you have seen textbook authors claim that with mounting supporting evidence hypotheses become theories, which in turn become laws, or give examples of the scientific method in which they fail to recognize the crucial difference between hypotheses and predictions (cf. Gibbs and Lawson 1992).

What college student has not heard about null hypotheses, which are not hypotheses at all. Instead they are null predictions (e.g., no significant difference should be found in the incidence of connective-tissue disease between women with and without breast implants). Little wonder that many students—and the general public—are often confused.

Another problem is that many instructors "cover" so much content that they do not leave time to discuss issues related to the nature of science. Also, the lab is often seen as an opportunity to support lecture topics rather than do real inquiries. To help solve this problem in our nonmajor courses, we no longer try to closely articulate lecture and lab so that when students need to take two or three weeks to answer a particularly difficult question in lab, they can take the time to do so.

Another threat to success is the current rush to incorporate high-tech machines such as computers and videodisc players into instructional settings. These devices may prove beneficial, but only so long as they do not replace actual hands-on, minds-on inquiries that allow students to generate and test alternative hypotheses and theories. Indeed, we would do well to keep firmly in mind the American Association for the Advancement of Science's central teaching principle which states that: "Teaching should be consistent with the nature of scientific inquiry" (AAAS 1989).

Many introductory college biology courses suffer from another problem. Having been designed largely by subject-matter experts, the courses are often structured to make sense from an already knowledgeable instructor's perspective, but not necessarily from an inquiring learner's perspective. Thus, the courses typically take a "micro-to-macro" approach, which begins at the highly-abstract and theoretical atomic and molecular levels and only later addresses more familiar and less abstract topics at the organism, population, and community levels.

Some recent textbooks have tried to remedy this problem by taking a "macro-to-micro" approach. Thus, they start big at the biome level and work their way down to ecosystems, communities, populations, organisms, and so forth. But this approach also fails to recognize that inquiry progresses from the familiar and concrete to the unfamiliar and abstract. Students are organisms, not biomes, so student inquiries should start at the organism level and then move toward either progressively smaller or progressively larger levels of organization.

Indeed, here the history of science has much to offer in terms of helping us identify "natural" routes of inquiry, routes that past scientists have taken and routes that present students can also take—routes that should lead to scientific literacy. That is, to students who know what science is and how to do it. ❑

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