CHAPTER 2

Science as a Way of Knowing: Critical Thinking about the Environment

Environmental science poses challenges to traditional science, as these students taking a field course in ecology are finding out. No data were available to tell them about the age of the forests or the grasses growing on the dunes. It's also more difficult to apply the scientific method when you are working in the field rather than in the controlled environment of a laboratory.

LEARNING OBJECTIVES

Science is a process of refining our understanding of nature through continual questioning and active investigation. It is more than a collection of facts to be memorized. After reading this chapter, you should understand that . . .

- Thinking about environmental issues requires thinking scientifically;
- We acquire scientific knowledge of the natural world through observations. The conclusions that we draw from these observations can be stated as hypotheses, theories, and scientific "laws." If they can be disproved, they are scientific. If they can't, they are not;
- Scientific understanding is not fixed; it changes over time as new data, observations, theories, and tests become available;
- Deductive and inductive reasoning are different, and we need to use both in scientific thinking;
- Every measurement involves some degree of approximation—that is, uncertainty—and a measurement without a statement about its degree of uncertainty is meaningless;
- Technology, the application of scientific knowledge, is not science, but science and technology interact, stimulating growth in each other;
- Decision-making about environmental issues involves society, politics, culture, economics, and values, as well as scientific information;
- Environmental scientific findings often get politicized when the use of scientific information is guided by a political goal and only data supporting that goal are selected;
- Forms of life seem so incredible and so well fitted to their environment that we wonder how they have come about. This question leads us to seek to understand different ways of knowing.

CASE STUDY

Birds at Mono Lake: Applying Science to Solve an Environmental Problem

Mono Lake is a large salt lake in California, just east of the Sierra Nevada and across these mountains from Yosemite National Park (Figure 2.1). More than a million birds use the lake; some feed and nest there, some stop on their migrations to feed. Within the lake, brine shrimp and brine fly larvae grow in great abundance, providing food for the birds. The shrimp and fly larvae, in turn, feed on algae and bacteria that grow in the lake (Figure 2.2).

The lake persisted for thousands of years in a desert climate because streams from the Sierra Nevada—fed by mountain snow and rain—flowed into it. But in the 1940s the city of Los Angeles diverted all stream water—beautifully clear water—to provide 17% of the water supply for the city. The lake began to dry out. It covered 60,000 acres in the 1940s, but only 40,000 by the 1980s.

Environmental groups expressed concern that the lake would soon become so salty and alkaline that all the brine shrimp and flies—food for the birds—would die, the birds would no longer be able to nest or feed there, and the beautiful lake would become a hideous eyesore—much like what happened to the Aral Sea in Asia. The Los Angeles Department of Water and Power argued that everything would be all right because rain falling directly on the lake and water flowing underground would provide ample water for the lake. People were unconvinced. “Save Mono Lake” became a popular bumper sticker in California, and the argument about the future of the lake raged for more than a decade.

Scientific information was needed to answer key questions: Without stream input, how small would the lake become? Would it really become too salty and alkaline for the shrimp, fly larvae, algae, and bacteria? If so, when?

The state of California set up a scientific panel to study the future of Mono Lake. The panel discovered that two crucial pieces of knowledge necessary to answer these questions had not been studied: the size and shape of the basin of the lake (so one could determine the lake’s volume and, from this, how its salinity and alkalinity would change) and the rate at which water evaporated from the lake (to determine whether and how fast the lake would become too dry to sustain life within it). New research was commissioned that answered these questions. The answers: By about the turn of the 21st century the lake would become so small that it would be too salty for the shrimp, fly larvae, algae, and bacteria.[1]

With this scientific information in hand, the courts decided that Los Angeles would have to stop the removal of water that flowed into Mono Lake. By 2008 the lake still had not recovered to the level required by the courts, indicating that diversion of water had been undesirable for the lake and its ecosystem.

Scientific information had told Californians what would happen, when it would likely happen, and what management approaches were possible. Science was essential to finding a solution that would work. But ultimately

FIGURE 2.1 **Mono Lake’s watershed below the beautiful east slope of the Sierra Nevada.** Streams flowing into the lake are visible as winding blue lines on the lower slopes. The lake and its sandy beaches form the flatlands in the mid-distance.

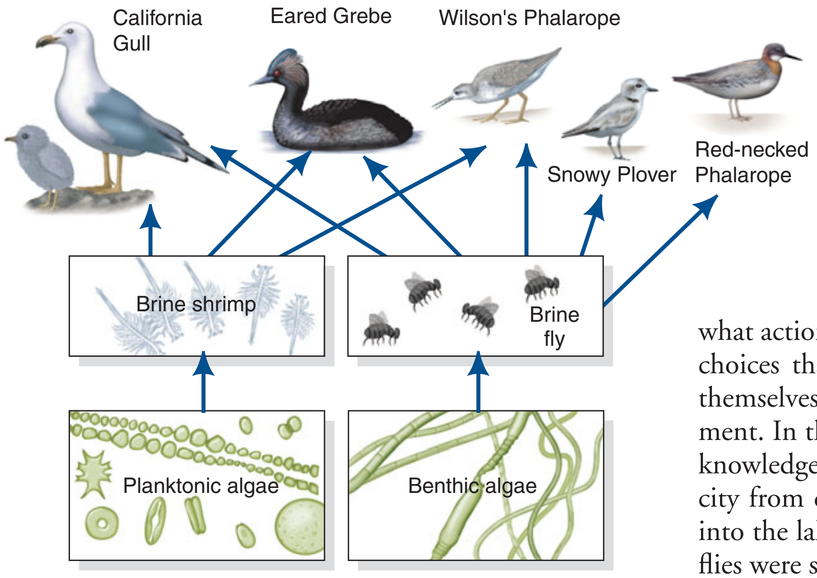

FIGURE 2.2 **The Mono Lake food chain.** The arrows show who feeds on whom. Just five species of birds are the top predators. This lake is one of the world's simpler ecosystems.

what actions to take, given this scientific knowledge, were choices that depended on values people held regarding themselves, their wants and desires, and the environment. In the end, decisions based on values and scientific knowledge were made by the courts, which stopped the city from diverting any of the stream waters that flowed into the lake. The birds, scenery, brine shrimp, and brine flies were saved.[2]

2.1 Understanding What Science Is—and What It Isn't

As the Mono Lake case study illustrates, modern civilization depends on science. The complexity of environmental sciences raises two fundamental questions: How does science differ from other ways of knowing? And how can we use science to answer practical questions about our effects on nature and what actions we should take to solve environmental problems?

Thinking about the environment is as old as our first human ancestors. Before humans developed the technology to deal with their environment, their very survival depended on knowledge of it. The environment also plays a crucial role in the development of each of us; normal human development does not occur in the absence of environmental stimuli.

However, thinking *scientifically* about the environment is only as old as science itself. Science had its roots in the ancient civilizations of Babylonia and Egypt, where observations of the environment were carried out primarily for practical reasons, such as planting crops, or for religious reasons, such as using the positions of the planets and stars to predict human events. Ancient precursors of science differed from modern science in that they did not distinguish between science and technology, nor between science and religion.

These distinctions first appeared in classical Greek science. Because of their general interest in ideas, the Greeks developed a more theoretical approach to science, in which knowledge for its own sake became the primary goal. At the same time, their philosophical approach began to move science away from religion and toward philosophy.

Modern science is usually considered to have begun toward the end of the 16th and the beginning of the 17th centuries with the development of the **scientific method** by Gilbert (magnets), Galileo (physics of motion), and Harvey (circulation of blood). Earlier classical scientists had asked "Why?" in the sense of "For what purpose?" But these three made important discoveries by asking "How?" in the sense of "How does it work?" Galileo also pioneered in the use of numerical observations and mathematical models. The scientific method, which quickly proved very successful in advancing knowledge, was first described explicitly by Francis Bacon in 1620. Although not a practicing scientist himself, Bacon recognized the importance of the scientific method, and his writings did much to promote scientific research.[3]

Our cultural heritage, therefore, gives us two ways of thinking about the environment: the kind of thinking we do in everyday life and the kind of thinking scientists try to do (Table 2.1). There are crucial differences between these two ways of thinking, and ignoring these differences can lead to invalid conclusions and serious errors in making critical decisions about the environment.

We can look at the world from many points of view, including religious, aesthetic, and moral. They are not science, however, because they are based ultimately on faith, beliefs, and cultural and personal choices, and are not open to disproof in the scientific sense. The distinction between a scientific statement and a nonscientific statement is not a value judgment—there is no implication that science is the only "good" kind of knowledge. The distinction is simply a philosophical one about kinds of knowledge and logic. Each way of viewing the world gives us a different way of perceiving and of making sense of our world, and each is valuable to us.

Table 2.1 KNOWLEDGE IN EVERYDAY LIFE COMPARED WITH KNOWLEDGE IN SCIENCE

FACTOR IN	EVERYDAY LIFE	AND IN SCIENCE
Goal	To lead a satisfying life (implicit)	To know, predict, and explain (explicit)
Requirements	Context-specific knowledge; no complex series of inferences; can tolerate ambiguities and lack of precision	General knowledge; complex, logical sequences of inferences, must be precise and unambiguous
Resolution of questions	Through discussion, compromise, consensus	Through observation, experimentation, logic
Understanding	Acquired spontaneously through interacting with world and people; criteria not well defined	Pursued deliberately; criteria clearly specified
Validity	Assumed, no strong need to check; based on observations, common sense, tradition, authorities, experts, social mores, faith	Must be checked; based on replications, converging evidence, formal proofs, statistics, logic
Organization of knowledge	Network of concepts acquired through experience; local, not integrated	Organized, coherent, hierarchical, logical; global, integrated
Acquisition of knowledge	Perception, patterns, qualitative; subjective	Plus formal rules, procedures, symbols, statistics, mental models; objective
Quality control	Informal correction of errors	Strict requirements for eliminating errors and making sources of error explicit

Source: Based on F. Reif and J.H. Larkin, "Cognition in Scientific and Everyday Domains: Comparison and Learning Implications," *Journal of Research in Science Teaching* 28(9), pp. 733–760. Copyright © 1991 by National Association for Research in Science Teaching. Reprinted by permission of John Wiley & Sons.

Science as a Way of Knowing

Science is a process, a way of knowing. It results in conclusions, generalizations, and sometimes scientific theories and even scientific laws. *Science begins with questions arising from curiosity about the natural world*, such as: How many birds nest at Mono Lake? What species of algae live in the lake? Under what conditions do they live?

Modern science does not deal with things that cannot be tested by observation, such as the ultimate purpose of life or the existence of a supernatural being. Science also does not deal with questions that involve values, such as standards of beauty or issues of good and evil—for example, whether the scenery at Mono Lake is beautiful. On the other hand, the statement that "more than 50% of the people who visit Mono Lake find the scenery beautiful" is a hypothesis (discussed later) that can be tested by public-opinion surveys and can be treated as a scientific statement if the surveys confirm it.

Disprovability

Here's the key to science: It is generally agreed today that the essence of the scientific method is **disprovability** (see Figure 2.3, a diagram that will be helpful throughout this chapter). A statement can be termed "scientific" if someone can state a method of disproving it. If no one can think of such a test, then the statement is said to be nonscientific. Consider, for example, the crop circles discussed in A Closer Look 2.1. One Web site says that some people believe the crop circles are a "spiritual nudge . . . designed to awaken us to our larger context and milieu, which is none other than our collective earth soul." Whether or not this is true, it does not seem open to disproof.

Science is a process of discovery—a continuing process whose essence is change in ideas. The fact that scientific ideas change is frustrating. Why can't scientists agree on what is the best diet for people? Why is a chemical considered dangerous in the environment for a while and then determined not to be? Why do scientists in one decade consider forest fires undesirable disturbances and in a later decade decide forest fires are natural and in fact important? Are we causing global warming or not? And on and on. Can't scientists just find out the truth and give us the final word on all these questions once and for all, and agree on it?

The answer is no—because science is a continuing adventure during which scientists make better and better approximations of how the world works. Sometimes changes in ideas are small, and the major context remains the same. Sometimes a science undergoes a fundamental revolution in ideas.

Science makes certain assumptions about the natural world: that events in the natural world follow patterns that can be understood through careful observation and scientific analysis, which we will describe later; and that these basic patterns and the rules that describe them are the same throughout the universe.

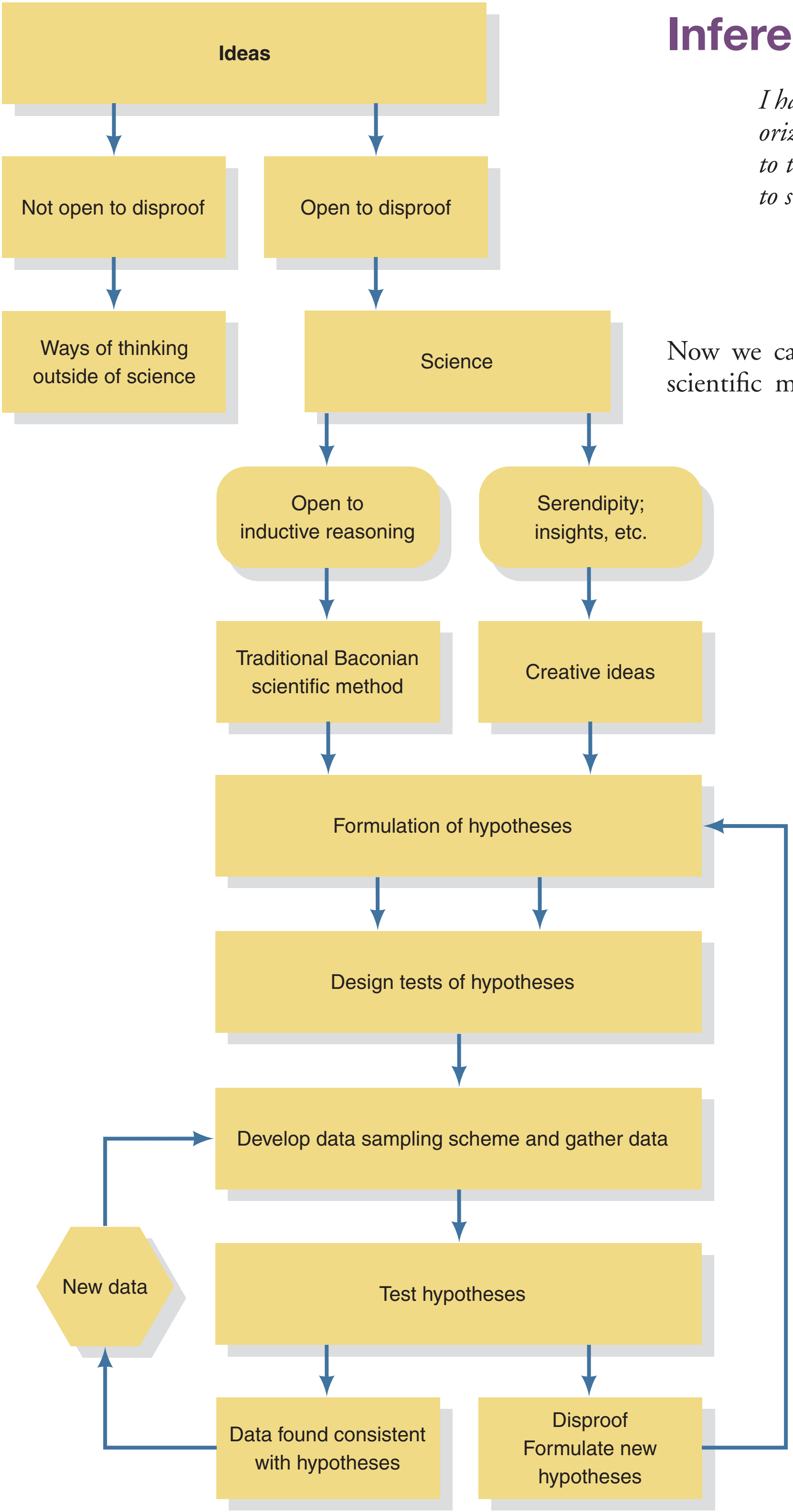

FIGURE 2.3 **Schematic diagram of the scientific method.** This diagram shows the steps in the scientific method, both traditional and nontraditional, as explained in the text.

2.2 Observations, Facts, Inferences, and Hypotheses

> *I have no data yet. It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.*
>
> —Sherlock Holmes,
> in Sir Arthur Conan Doyle's
> *A Scandal in Bohemia*

Now we can turn to the specific characteristics of the scientific method. (The steps in the scientific method are shown in Table 2.2.) It is important to distinguish between observations and inferences. **Observations**, the basis of science, may be made through any of the five senses or by instruments that measure beyond what we can sense. **Inferences** are generalizations that arise from a set of observations. When everyone or almost everyone agrees with what is observed about a particular thing, the inference is often called a **fact**.

We might *observe* that a substance is a white, crystalline material with a sweet taste. We might *infer* from these observations alone that the substance is sugar. Before this inference can be accepted as fact, however, it must be subjected to further tests. Confusing observations with inferences and accepting untested inferences as facts are kinds of sloppy thinking described as "Thinking makes it so." When scientists wish to test an inference, they convert it into a **hypothesis**, which is a statement that can be disproved. The hypothesis continues to be accepted until it is disproved.

For example, a scientist is trying to understand how a plant's growth will change with the amount of light it receives. She proposed a hypothesis that a plant can use only so much light and no more—it can be "saturated" by an abundance of light. She measures the rate of photosynthesis at a variety of light intensities. The rate of photosynthesis is called the **dependent variable** because it is affected by, and in this sense depends on, the amount of light, which is called the **independent variable**. The independent variable is also sometimes called a **manipulated variable**

Table 2.2 STEPS IN THE SCIENTIFIC METHOD (TERMS USED HERE ARE DEFINED IN THE TEXT.)

1. Make observations and develop a question about the observations.
2. Develop a tentative answer to the question—a hypothesis.
3. Design a controlled experiment to test the hypothesis (implies identifying and defining independent and dependent variables).
4. Collect data in an organized form, such as a table.
5. Interpret the data visually (through graphs), quantitatively (using statistical analysis) and/or by other means.
6. Draw a conclusion from the data.
7. Compare the conclusion with the hypothesis and determine whether the results support or disprove the hypothesis.
8. If the hypothesis is consistent with observations in some limited experiments, conduct additional experiments to test it further. If the hypothesis is rejected, make additional observations and construct a new hypothesis.

because it is deliberately changed, or manipulated, by the scientist. The dependent variable is then referred to as a **responding variable**—one that responds to changes in the manipulated variable. These values are referred to as *data* (singular: *datum*). They may be numerical, **quantitative data**, or nonnumerical, **qualitative data**. In our example, qualitative data would be the species of a plant; quantitative data would be the tree's mass in grams or the diameter in centimeters. The result of the scientist's observations: The hypothesis is confirmed: The rate of photosynthesis increases to a certain level and does not go higher at higher light intensities (Figure 2.4).

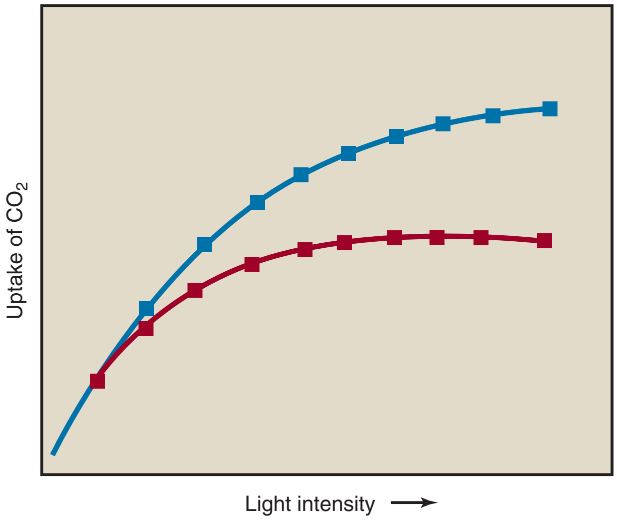

FIGURE 2.4 Dependent and independent variables: Photosynthesis as affected by light. In this diagram, photosynthesis is represented by carbon dioxide (CO_2) uptake. Light is the independent variable, uptake is the dependent variable. The blue and red lines represent two plants with different responses to light.

Controlling Variables

In testing a hypothesis, a scientist tries to keep all relevant **variables** constant except for the independent and dependent variables. This practice is known as *controlling variables*. In a **controlled experiment**, the experiment is compared to a standard, or control—an exact duplicate of the experiment except for the one variable being tested (the **independent variable**). Any difference in outcome (dependent variable) between the experiment and the control can be attributed to the effect of the independent variable.

An important aspect of science, but one frequently overlooked in descriptions of the scientific method, is the need to define or describe variables in exact terms that all scientists can understand. The least ambiguous way to define or describe a variable is in terms of what one would have to do to duplicate the measurement of that variable. Such definitions are called **operational definitions**. Before carrying out an experiment, both the independent and dependent variables must be defined operationally. Operational definitions allow other scientists to repeat experiments exactly and to check on the results reported.

Science is based on **inductive reasoning**, also called *induction*: It begins with specific observations and then extends to generalizations, which may be disproved by testing them. If such a test cannot be devised, then we cannot treat the generalization as a scientific statement. Although new evidence can disprove existing scientific theories, science can never provide absolute proof of the truth of its theories.

The Nature of Scientific Proof

One source of serious misunderstanding about science is the use of the word *proof*, which most students encounter in mathematics, particularly in geometry. Proof in mathematics and logic involves reasoning from initial definitions and assumptions. If a conclusion follows logically from these assumptions, or premises, we say it is proven. This process is known as **deductive reasoning**. An example of deductive reasoning is the following syllogism, or series of logically connected statements:

> *Premise: A straight line is the shortest distance between two points.*
>
> *Premise: The line from A to B is the shortest distance between points A and B.*
>
> *Conclusion: Therefore, the line from A to B is a straight line.*

Note that the conclusion in this syllogism follows directly from the premises.

Deductive proof does not require that the premises be true, only that the reasoning be foolproof. Statements that are logically valid but untrue can result from false premises, as in the following example (Figure 2.5):

> *Premise: Humans are the only toolmaking organisms.*
>
> *Premise: The woodpecker finch uses tools.*
>
> *Conclusion: Therefore, the woodpecker finch is a human being.*

In this case, the concluding statement must be true if both of the preceding statements are true. However, we know that the conclusion is not only false but ridiculous. If the second statement is true (which it is), then the first cannot be true.

The rules of deductive reasoning govern only the process of moving from premises to conclusion. *Science, in contrast, requires not only logical reasoning but also correct premises*. Returning to the example of the woodpecker finch, to be scientific the three statements should be expressed conditionally (that is, with reservation):

> *If humans are the only toolmaking organisms*
> *and*
> *the woodpecker finch is a toolmaker,*
> *then*
> *the woodpecker finch is a human being.*

When we formulate generalizations based on a number of observations, we are engaging in inductive reasoning. To illustrate: One of the birds that feeds at Mono Lake is the eared grebe. The “ears” are a fan of golden feathers that occur behind the eyes of males during the breeding season. Let us define birds with these golden feather fans as eared grebes (Figure 2.6). If we always observe that the breeding male grebes have this feather fan, we may make the inductive statement “All male eared grebes have golden feathers during the breeding season.” What we really mean is “All of the male eared grebes *we*

FIGURE 2.5 **A woodpecker finch in the Galápagos Islands** uses a twig to remove insects from a hole in a tree, demonstrating tool use by nonhuman animals. Because science is based on observations, its conclusions are only as true as the premises from which they are deduced.

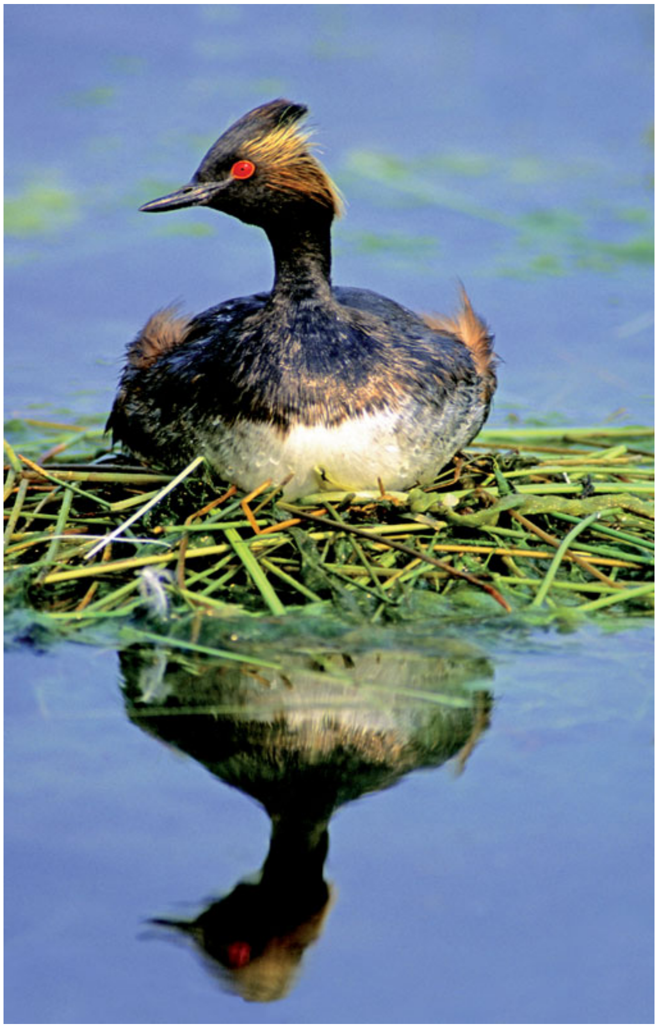

FIGURE 2.6 **Male eared grebe in breeding season.**

have seen in the breeding season have golden feathers." We never know when our very next observation will turn up a bird that is like a male eared grebe in all ways except that it lacks these feathers in the breeding season. This is not impossible; it could occur somewhere due to a mutation.

Proof in inductive reasoning is therefore very different from proof in deductive reasoning. When we say something is proven in induction, what we really mean is that it has a very high degree of probability. Probability is a way of expressing our certainty (or uncertainty)—our estimation of how good our observations are, how confident we are of our predictions.

Theory in Science and Language

A common misunderstanding about science arises from confusion between the use of the word *theory* in science and its use in everyday language. A **scientific theory** is a grand scheme that relates and explains many observations and is supported by a great deal of evidence. In contrast, in everyday usage a theory can be a guess, a hypothesis, a prediction, a notion, a belief. We often hear the phrase "It's just a theory." That may make sense in everyday conversation but not in the language of science. In fact, theories have tremendous prestige and are considered the greatest achievements of science.[3]

Further misunderstanding arises when scientists use the word *theory* in several different senses. For example, we may encounter references to a currently accepted, widely supported theory, such as the theory of evolution by natural selection; a discarded theory, such as the theory of inheritance of acquired characteristics; a new theory, such as the theory of evolution of multicellular organisms by symbiosis; and a model dealing with a specific or narrow area of science, such as the theory of enzyme action.[4]

One of the most important misunderstandings about the scientific method pertains to the relationship between research and theory. Theory is usually presented as growing out of research, but in fact theories also guide research. When a scientist makes observations, he or she does so in the context of existing theories. At times, discrepancies between observations and accepted theories become so great that a scientific revolution occurs: The old theories are discarded and are replaced with new or significantly revised theories.[5]

Knowledge in an area of science grows as more hypotheses are supported. Ideally, scientific hypotheses are continually tested and evaluated by other scientists, and this provides science with a built-in self-correcting feedback system. This is an important, fundamental feature of the scientific method. If you are told that scientists have reached a consensus about something, you want to check carefully to see if this feedback process has been used correctly and is still possible. If not, what began as science can be converted to ideology—a way that certain individuals, groups, or cultures may think despite evidence to the contrary.

Models and Theory

Scientists use accumulated knowledge to develop explanations that are consistent with currently accepted hypotheses. Sometimes an explanation is presented as a model. A **model** is "a deliberately simplified construct of nature."[6] It may be a physical working model, a pictorial model, a set of mathematical equations, or a computer simulation. For example, the U.S. Army Corps of Engineers has a physical model of San Francisco Bay. Open to the public to view, it is a miniature in a large aquarium with the topography of the bay reproduced to scale and with water flowing into it in accordance with tidal patterns. Elsewhere, the Army Corps develops mathematical equations and computer simulations, which are models and attempt to explain some aspects of such water flow.

As new knowledge accumulates, models may no longer be consistent with observations and may have to be revised or replaced, with the goal of finding models more consistent with nature.[5] Computer simulation of the atmosphere has become important in scientific analysis of the possibility of global warming. Computer simulation is becoming important for biological systems as well, such as simulations of forest growth (Figure 2.7).

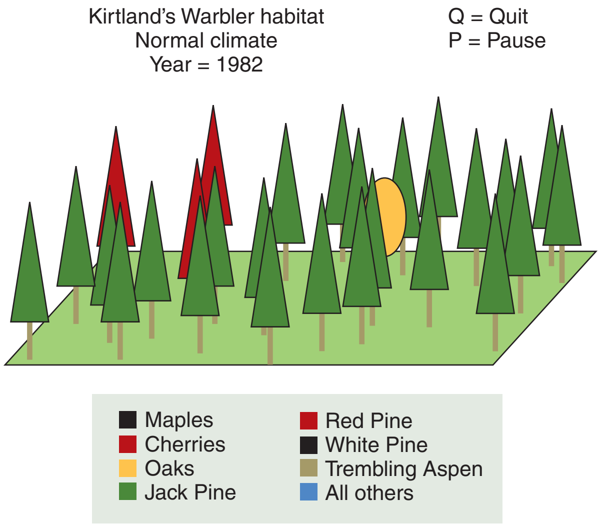

FIGURE 2.7 A computer simulation of forest growth. Shown here is a screen display of individual trees whose growth is forecast year by year, depending on environmental conditions. In this computer run, only three types of trees are present. This kind of model is becoming increasingly important in environmental sciences. (*Source: JABOWA-II* by D.B. Botkin. Copyright © 1993, 2009 by D.B. Botkin.)

A CLOSER LOOK 2.1

The Case of the Mysterious Crop Circles

For 13 years, circular patterns appeared "mysteriously" in grainfields in southern England (Figure 2.8). Proposed explanations included aliens, electromagnetic forces, whirlwinds, and pranksters. The mystery generated a journal and a research organization headed by a scientist, as well as a number of books, magazines, and clubs devoted solely to crop circles. Scientists from Great Britain and Japan brought in scientific equipment to study the strange patterns. Then, in September 1991, two men confessed to having created the circles by entering the fields along paths made by tractors (to disguise their footprints) and dragging planks through the fields. When they made their confession, they demonstrated their technique to reporters and some crop-circle experts.[4, 5]

Despite their confession, some people still believe that the crop circles were caused by something else, and crop-circle organizations not only still exist but also now have Web sites. One report published on the World Wide Web in 2003 stated that "strange orange lightning" was seen one evening and that crop circles appeared the next day.[7, 8]

How is it that so many people, including some scientists, still take those English crop circles seriously? Probably some of these people misunderstand the scientific method and used it incorrectly—and some simply want to believe in a mysterious cause and therefore chose to reject scientific information. We run into this way of thinking frequently with environmental issues. People often believe that some conclusions or some action is good, based on their values. They wish it were so, and decide therefore that it must be so. The false logic here can be phrased: *If it sounds good, it must be good, and if it must be good, we must make it happen.*

FIGURE 2.8 **(a)** A crop circle close up at the Vale of Pewsey in southern England in July 1990. **(b)** Crop circles seen from the air make distinctive patterns.

Some Alternatives to Direct Experimentation

Environmental scientists have tried to answer difficult questions using several approaches, including historical records and observations of modern catastrophes and disturbances.

Historical Evidence

Ecologists have made use of both human and ecological historical records. A classic example is a study of the history of fire in the Boundary Waters Canoe Area (BWCA) of Minnesota, 1 million acres of boreal forests, streams, and lakes well known for recreational canoeing.

Murray ("Bud") Heinselman had lived near the BWCA for much of his life and was instrumental in having it declared a wilderness area. A forest ecological scientist, Heinselman set out to determine the past patterns of fires in this wilderness. Those patterns are important in maintaining the wilderness. If the wilderness has been characterized by fires of a specific frequency, then one can argue that this frequency is necessary to maintain the area in its most "natural" state.

Heinselman used three kinds of historical data: written records, tree-ring records, and buried records (fossil and prefossil organic deposits). Trees of the boreal forests, like most trees that are conifers or angiosperms (flowering plants),

FIGURE 2.9 Cross section of a tree showing fire scars and tree rings. Together these allow scientists to date fires and to average the time between fires.

produce annual growth rings. If a fire burns through the bark of a tree, it leaves a scar, just as a serious burn leaves a scar on human skin. The tree grows over the scar, depositing a new growth ring for each year. (Figure 2.9 shows fire scars and tree rings on a cross section of a tree.) By examining cross sections of trees, it is possible to determine the date of each fire and the number of years between fires. From written and tree-ring records, Heinselman found that the frequency of fires had varied over time but that since the 17th century the BWCA forests had burned, on average, once per century. Furthermore, buried charcoal dated using carbon-14 revealed that fires could be traced back more than 30,000 years.[9]

The three kinds of historical records provided important evidence about fire in the history of the BWCA. At the time Heinselman did his study, the standard hypothesis was that fires were bad for forests and should be suppressed. The historical evidence provided a disproof of this hypothesis. It showed that fires were a natural and an integral part of the forest and that the forest had persisted with fire for a very long time. Thus, the use of historical information meets the primary requirement of the scientific method—the ability to disprove a statement. Historical evidence is a major source of data that can be used to test scientific hypotheses in ecology.

Modern Catastrophes and Disturbances as Experiments

Sometimes a large-scale catastrophe provides a kind of modern ecological experiment. The volcanic eruption of Mount St. Helens in 1980 supplied such an experiment, destroying vegetation and wildlife over a wide area. The recovery of plants, animals, and ecosystems following this explosion gave scientists insights into the dynamics of ecological systems and provided some surprises. The main surprise was how quickly vegetation recovered and wildlife returned to parts of the mountain. In other ways, the recovery followed expected patterns in ecological succession (see Chapters 5 and 12).

It is important to point out that the greater the quantity and the better the quality of ecological data prior to such a catastrophe, the more we can learn from the response of ecological systems to the event. This calls for careful monitoring of the environment.

Uncertainty in Science

In science, when we have a fairly high degree of confidence in our conclusions, we often forget to state the degree of certainty or uncertainty. Instead of saying, "There is a 99.9% probability that . . . ," we say, "It has been proved that . . ." Unfortunately, many people interpret this as a deductive statement, meaning the conclusion is absolutely true, which has led to much misunderstanding about science. Although science begins with observations and therefore inductive reasoning, deductive reasoning is useful in helping scientists analyze whether conclusions based on inductions are logically valid. *Scientific reasoning combines induction and deduction*—different but complementary ways of thinking.

Leaps of Imagination and Other Nontraditional Aspects of the Scientific Method

What we have described so far is the classic scientific method. Scientific advances, however, often happen somewhat differently. They begin with instances of insight—leaps of imagination that are then subjected to the stepwise inductive process. And some scientists have made major advances by being in the right place at the right time, noticing interesting oddities, and knowing how to put these clues together. For example, penicillin was discovered "by accident" in 1928 when Sir Alexander Fleming was studying the pus-producing bacterium *Staphylococcus aureus*. When a culture of these bacteria was accidentally contaminated by the green fungus *Penicillium notatum*, Fleming noticed that the bacteria did not grow in areas of the culture where the fungus grew. He isolated the mold, grew it in a fluid medium, and found that it produced a substance that killed many of the bacteria that caused diseases. Eventually this discovery led other scientists to develop an injectable agent to treat diseases. *Penicillium notatum* is a common mold found on stale bread. No doubt many others had seen it, perhaps even noticing that other strange growths on bread did not overlap with *Penicillium notatum*. But it took Fleming's knowledge and observational ability for this piece of "luck" to occur.

2.3 Measurements and Uncertainty

A Word about Numbers in Science

We communicate scientific information in several ways. The written word is used for conveying synthesis, analysis, and conclusions. When we add numbers to our analysis, we obtain another dimension of understanding that goes beyond qualitative understanding and synthesis of a problem. Using numbers and statistical analysis allows us to visualize relationships in graphs and make predictions. It also allows us to analyze the strength of a relationship and in some cases discover a new relationship.

People in general put more faith in the accuracy of measurements than do scientists. Scientists realize that all measurements are only approximations, limited by the accuracy of the instruments used and the people who use them. Measurement uncertainties are inevitable; they can be reduced but never completely eliminated. For this reason, *a measurement is meaningless unless it is accompanied by an estimate of its uncertainty.*

Consider the loss of the *Challenger* space shuttle in 1986, the first major space shuttle accident, which appeared to be the result of the failure of rubber O-rings that were supposed to hold sections of rockets together. Imagine a simplified scenario in which an engineer is given a rubber O-ring used to seal fuel gases in a space shuttle. The engineer is asked to determine the flexibility of the O-rings under different temperature conditions to help answer two questions: At what temperature do the O-rings become brittle and subject to failure? And at what temperature(s) is it unsafe to launch the shuttle? After doing some tests, the engineer says that the rubber becomes brittle at –1°C (30°F). So, can you assume it is safe to launch the shuttle at 0°C (32°F)?

At this point, you do not have enough information to answer the question. You assume that the temperature data may have some degree of uncertainty, but you have no idea how great a degree. Is the uncertainty ±5°C, ±2°C, or ±0.5°C? To make a reasonably safe and economically sound decision about whether to launch the shuttle, you must know the amount of uncertainty of the measurement.

Dealing with Uncertainties

There are two sources of uncertainty. One is the real variability of nature. The other is the fact that every measurement has some error. Measurement uncertainties and other errors that occur in experiments are called **experimental errors**. Errors that occur consistently, such as those resulting from incorrectly calibrated instruments, are **systematic errors**.

Scientists traditionally include a discussion of experimental errors when they report results. Error analysis often leads to greater understanding and sometimes even to important discoveries. For example, scientists discovered the eighth planet in our solar system, Neptune, when they investigated apparent inconsistencies—observed "errors"—in the orbit of the seventh planet, Uranus.

We can reduce measurement uncertainties by improving our measurement instruments, standardizing measurement procedures, and using carefully designed experiments and appropriate statistical procedures. Even then, however, uncertainties can never be completely eliminated. Difficult as it is for us to live with uncertainty, that is the nature of nature, as well as the nature of measurement and of science. Our awareness of these uncertainties should lead us to read reports of scientific studies critically, whether they appear in science journals or in popular magazines and newspapers. (See A Closer Look 2.2.)

Accuracy and Precision

A friend inherited some land on an island off the coast of Maine. However, the historical records were unclear about the land's boundaries, and to sell any portion of the land, he first had to determine where his neighbor's land ended and his began. There were differences of opinion about this. In fact, some people said one boundary went right through the house, which would have caused a lot of problems! Clearly what was needed was a good map that everybody could agree on, so our friend hired a surveyor to determine exactly where the boundaries were.

The original surveyor's notes from the early 19th century had vague guidelines, such as "beginning at the mouth of Marsh brook on the Eastern side of the bars at a stake and stones. . . thence running South twenty six rods to a stake & stones. . . ." Over time, of course, the shore, the brook, its mouth, and the stones had moved and the stakes had disappeared. The surveyor was clear about the total distance (a rod, by the way, is an old English measure equal to 16.5 feet or 5.02 meters), but "South" wasn't very specific. So where and in exactly which direction was the true boundary? (This surveyor's method was common in early-19th-century New England. One New Hampshire survey during that time began with "Where you and I were standing yesterday . . ." Another began, "Starting at the hole in the ice [on the pond] . . .").

The 21st-century surveyor who was asked to find the real boundary used the most modern equipment—laser and microwave surveying transits, GPS devices—so he knew where the line he measured went to in millimeters. He could remeasure his line and come within

A CLOSER LOOK 2.2

Measurement of Carbon Stored in Vegetation

A number of people have suggested that a partial solution to global warming might be a massive worldwide program of tree planting. Trees take carbon dioxide (an important greenhouse gas) out of the air in the process of photosynthesis. And because trees live a long time, they can store carbon for decades, even centuries. But how much carbon can be stored in trees and in all perennial vegetation? Many books and reports published during the past 20 years contained numbers representing the total stored carbon in Earth's vegetation, but all were presented without any estimate of error (Table 2.3). Without an estimate of that uncertainty, the figures are meaningless, yet important environmental decisions have been based on them.

Recent studies have reduced error by replacing guesses and extrapolations with scientific sampling techniques similar to those used to predict the outcomes of elections. Even these improved data would be meaningless, however, without an estimate of error. The new figures show that the earlier estimates were three to four times too large, grossly overestimating the storage of carbon in vegetation and therefore the contribution that tree planting could make in offsetting global warming.

Table 2.3 ESTIMATES OF ABOVEGROUND BIOMASS IN NORTH AMERICAN BOREAL FOREST

SOURCE	BIOMASS[a] (kg/m^2)	CARBON[b] (kg/m^2)	TOTAL BIOMASS[c] (10^9 metric tons)	TOTAL CARBON[c] (10^9 metric tons)
This study[d]	4.2 ± 1.0	1.9 ± 0.4	22 ± 5	9.7 ± 2
Previous estimates[e]				
1	17.5	7.9	90	40
2	15.4	6.9	79	35
3	14.8	6.7	76	34
4	12.4	5.6	64	29
5	5.9	2.7	30	13.8

Source: D.B. Botkin and L. Simpson, "The First Statistically Valid Estimate of Biomass for a Large Region," *Biogeochemistry* 9 (1990): 161–274. Reprinted by permission of Klumer Academic, Dordrecht, The Netherlands.

[a] Values in this column are for total aboveground biomass. Data from previous studies giving total biomass have been adjusted using the assumption that 23% of the total biomass is in below-ground roots. Most references use this percentage; Leith and Whittaker use 17%. We have chosen to use the larger value to give a more conservative comparison.

[b] Carbon is assumed to be 45% of total biomass following R.H. Whittaker, *Communities and Ecosystems* (New York: Macmillan, 1974).

[c] Assuming our estimate of the geographic extent of the North American boreal forest: 5,126,427 km^2 (324,166 mi^2).

[d] Based on a statistically valid survey; aboveground woodplants only.

[e] Lacking estimates of error: Sources of previous estimates by number (1) G.J. Ajtay, P. Ketner, and P. Duvigneaud, "Terrestial Primary Production and Phytomass," in B. Bolin, E.T. Degens, S. Kempe, and P. Ketner, eds., *The Global Carbon Cycle* (New York: Wiley, 1979), pp. 129–182. (2) R.H. Whittaker and G.E. Likens, "Carbon in the Biota," in G.M. Woodwell and E.V. Pecam, eds., *Carbon and the Biosphere* (Springfield, VA: National Technical Information Center, 1973), pp. 281–300. (3) J.S. Olson, H.A. Pfuderer, and Y.H. Chan, *Changes in the Global Carbon Cycle and the Biosphere*, ORNL/EIS-109 (Oak Ridge, TN: Oak Ridge National Laboratory, 1978). (4) J.S. Olson, I.A. Watts, and L.I. Allison, *Carbon in Live Vegetation of Major World Ecosystems*, ORNL-5862 (Oak Ridge, TN: Oak Ridge National Laboratory, 1983). (5) G.M. Bonnor, *Inventory of Forest Biomass in Canada* (Petawawa, Ontario: Canadian Forest Service, Petawawa National Forest Institute, 1985).

millimeters of his previous location. But because the original starting point couldn't be determined within many meters, the surveyor didn't know where the true boundary line went; it was just somewhere within 10 meters or so of the line he had surveyed. So the end result was that even after this careful, modern, high-technology survey, nobody really knew where the original boundary lines went. Scientists would say that the modern surveyor's work was precise but not accurate. *Accuracy* refers to what we know; *precision* to how well we measure. With such things as this land survey, this is an important difference.

Accuracy also has another, slightly different scientific meaning. In some cases, certain measurements have been made very carefully by many people over a long period, and accepted values have been determined. In that kind of situation, *accuracy* means the extent to which a measurement agrees with the accepted value. But as before, *precision* retains its original meaning, the degree of exactness with which a quantity is measured. In the case of the land in Maine, we can say that the new measurement had no accuracy in regard to the previous ("accepted") value.

Although a scientist should make measurements as precisely as possible, this friend's experience with surveying his land shows us that it is equally important not to report measurements with more precision than they warrant. Doing so conveys a misleading sense of both precision and accuracy.

2.4 Misunderstandings about Science and Society

Science and Decision Making

Like the scientific method, the process of making decisions is sometimes presented as a series of steps:

1. Formulate a clear statement of the issue to be decided.
2. Gather the scientific information related to the issue.
3. List all alternative courses of action.
4. Predict the positive and negative consequences of each course of action and the probability that each consequence will occur.
5. Weigh the alternatives and choose the best solution.

Such a procedure is a good guide to rational decision making, but it assumes a simplicity not often found in real-world issues. It is difficult to anticipate all the potential consequences of a course of action, and unintended consequences are at the root of many environmental problems. Often the scientific information is incomplete and even controversial. For example, the insecticide DDT causes eggshells of birds that feed on insects to be so thin that unhatched birds die. When DDT first came into use, this consequence was not predicted. Only when populations of species such as the brown pelican became seriously endangered did people become aware of it.

In the face of incomplete information, scientific controversies, conflicting interests, and emotionalism, how can we make sound environmental decisions? We need to begin with the scientific evidence from all relevant sources and with estimates of the uncertainties in each. Avoiding emotionalism and resisting slogans and propaganda are essential to developing sound approaches to environmental issues. Ultimately, however, environmental decisions are policy decisions negotiated through the political process. Policymakers are rarely professional scientists; generally, they are political leaders and ordinary citizens. Therefore, the scientific education of those in government and business, as well as of all citizens, is crucial.

Science and Technology

Science is often confused with technology. As noted earlier, science is a search for understanding of the natural world, whereas technology is the application of scientific knowledge in an attempt to benefit people. Science often leads to technological developments, just as new technologies lead to scientific discoveries. The telescope began as a technological device, such as an aid to sailors, but when Galileo used it to study the heavens, it became a source of new scientific knowledge. That knowledge stimulated the technology of telescope-making, leading to the production of better telescopes, which in turn led to further advances in the science of astronomy.

Science is limited by the technology available. Before the invention of the electron microscope, scientists were limited to magnifications of 1,000 times and to studying objects about the size of one-tenth of a micrometer. (A micrometer is 1/1,000,000 of a meter, or 1/1,000 of a millimeter.) The electron microscope enabled scientists to view objects far smaller by magnifying more than 100,000 times. The electron microscope, a basis for new science, was also the product of science. Without prior scientific knowledge about electron beams and how to focus them, the electron microscope could not have been developed.

Most of us do not come into direct contact with science in our daily lives; instead, we come into contact with the products of science—technological devices such as computers, iPods, and microwave ovens. Thus, people tend to confuse the products of science with science itself. As you study science, it will help if you keep in mind the distinction between science and technology.

Science and Objectivity

One myth about science is the myth of objectivity, or value-free science—the notion that scientists are capable of complete objectivity independent of their personal values and the culture in which they live, and that science deals only with objective facts. Objectivity is certainly a goal of scientists, but it is unrealistic to think they can be totally free of influence by their social environments and personal values. It would be more realistic to admit that scientists do have biases and to try to identify these biases rather than deny or ignore them. In some ways, this situation is similar to that of measurement error: It is inescapable, and we can best deal with it by recognizing it and estimating its effects.

To find examples of how personal and social values affect science, we have only to look at recent controversies about environmental issues, such as whether or not to adopt more stringent automobile emission standards. Genetic engineering, nuclear power, global warming, and the preservation of threatened or endangered species involve conflicts among science, technology, and society. When we function as *scientists* in society, we want to explain the results of science objectively. As citizens who are not scientists, we want scientists to always be objective and tell us the truth about their scientific research.

That science is not entirely value-free should not be taken to mean that fuzzy thinking is acceptable in science. It is still important to think critically and logically about science and related social issues. Without the high standards of evidence held up as the norm for science, we run the risk of accepting unfounded ideas about the world. When we confuse what we would like to believe with what we have the evidence to believe, we have a weak basis for making critical environmental decisions that could have far-reaching and serious consequences.

The great successes of science, especially as the foundation for so many things that benefit us in modern technological societies—from cell phones to CAT scans to space exploration—give science and scientists a societal authority that makes it all the more difficult to know when a scientist might be exceeding the bounds of his or her scientific knowledge. It may be helpful to realize that scientists play three roles in our society: first, as researchers simply explaining the results of their work; second, as almost priestlike authorities who often seem to speak in tongues the rest of us can't understand; and third, as what we could call expert witnesses. In this third role, they will discuss broad areas of research that they are familiar with and that are within their field of study, but about which they may not have done research themselves. Like an expert testifying in court, they are basically saying to us, "Although I haven't done this particular research myself, my experience and knowledge suggest to me that . . ."

The roles of researcher and expert witness are legitimate as long as it is clear to everybody which role a scientist is playing. Whether you want a scientist to be your authority about everything, within science and outside of science, is a personal and value choice.

In the modern world, there is another problem about the role of scientists and science in our society. Science has been so potent that it has become fundamental to political policies. As a result, science can become politicized, which means that rather than beginning with objective inquiry, people begin with a belief about something and pick and choose only the scientific evidence that supports that belief. This can even be carried to the next step, where research is funded only if it fits within a political or an ethical point of view.

Scientists themselves, even acting as best they can *as* scientists, can be caught up in one way of thinking when the evidence points to another. These scientists are said to be working under a certain paradigm, a particular theoretical framework. Sometimes their science undergoes a paradigm shift: New scientific information reveals a great departure from previous ways of thinking and from previous scientific theories, and it is difficult, after working within one way of thinking, to recognize that some or all of their fundamentals must change. Paradigm shifts happen over and over again in science and lead to exciting and often life-changing results for us. The discovery and understanding of electricity are examples, as is the development of quantum mechanics in physics in the early decades of the 20th century.

We can never completely escape biases, intentional and unintentional, in fundamental science, its interpretation, and its application to practical problems, but understanding the nature of the problems that can arise can help us limit this misuse of science. The situation is complicated by legitimate scientific uncertainties and differences in scientific theories. It is hard for us, as citizens, to know when scientists are having a legitimate debate about findings and theories, and when they are disagreeing over personal beliefs and convictions that are outside of science. Because environmental sciences touch our lives in so many ways, because they affect things that are involved with choices and values, and because these sciences deal with phenomena of great complexity, the need to understand where science can go astray is especially important.

Science, Pseudoscience, and Frontier Science

Some ideas presented as scientific are in fact not scientific, because they are inherently untestable, lack empirical support, or are based on faulty reasoning or poor scientific methodology, as illustrated by the case of the mysterious crop circles (A Closer Look 2.1). Such ideas are referred to as pseudoscientific (the prefix *pseudo-* means false).

CRITICAL THINKING ISSUE

How Do We Decide What to Believe about Environmental Issues?

When you read about an environmental issue in a newspaper or magazine, how do you decide whether to accept the claims made in the article? Are they based on scientific evidence, and are they logical? Scientific evidence is based on observations, but media accounts often rely mainly on inferences (interpretations) rather than evidence. Distinguishing inferences from evidence is an important first step in evaluating articles critically. Second, it is important to consider the source of a statement. Is the source a reputable scientific organization or publication? Does the source have a vested interest that might bias the claims? When sources are not named, it is impossible to judge the reliability of claims. If a claim is based on scientific evidence presented logically from a reliable, unbiased source, it is appropriate to accept the claim tentatively, pending further information. Practice your critical evaluation skills by reading the article below and answering the critical thinking questions.

Critical Thinking Questions

1. What is the major claim made in the article?
2. What evidence does the author present to support the claim?
3. Is the evidence based on observations, and is the source of the evidence reputable and unbiased?
4. Is the argument for the claim, whether or not based on evidence, logical?
5. Would you accept or reject the claim?
6. Even if the claim were well supported by evidence based on good authority, why would your acceptance be only tentative?

CLUE FOUND IN DEFORMED FROG MYSTERY

BY MICHAEL CONLON

Reuters News Agency (as printed in the *Toronto Star*)
November 6, 1996

A chemical used for mosquito control could be linked to deformities showing up in frogs across parts of North America, though the source of the phenomenon remains a mystery. "We're still at the point where we've got a lot of leads that we're trying to follow but no smoking gun," says Michael Lannoo of Ball State University in Muncie, Ind. "There are an enormous number of chemicals that are being applied to the environment and we don't understand what the breakdown products of these chemicals are," says Lannoo, who heads the U.S. section of the worldwide Declining Amphibian Population Task Force.

He says one suspect chemical was methoprene, which produces a breakdown product resembling retinoic acid, a substance important in development. "Retinoic acid can produce in the laboratory all or a majority of the limb deformities that we're seeing in nature," he says. "That's not to say that's what's going on. But it is the best guess as to what's happening." Methoprene is used for mosquito control, among other things, Lannoo says.

Both the decline in amphibian populations and the deformities are of concern because frogs and related creatures are considered "sentinel" species that can provide early warnings of human risk. The skin of amphibians is permeable and puts them at particular risk to agents in the water.

Lannoo says limb deformities in frogs had been reported as far back as 1750, but the rate of deformities showing up today was unprecedented in some species. Some were showing abnormalities that affected more than half of the population of a species living in certain areas, he adds. He says he doubted that a parasite believed to have been the cause of some deformities in frogs in California was to blame for similar problems in Minnesota and nearby states. Deformed frogs have been reported in Minnesota, Wisconsin, Iowa, South Dakota, Missouri, California, Texas, Vermont, and Quebec. The deformities reported have included misshapen legs, extra limbs, and missing or misplaced eyes.

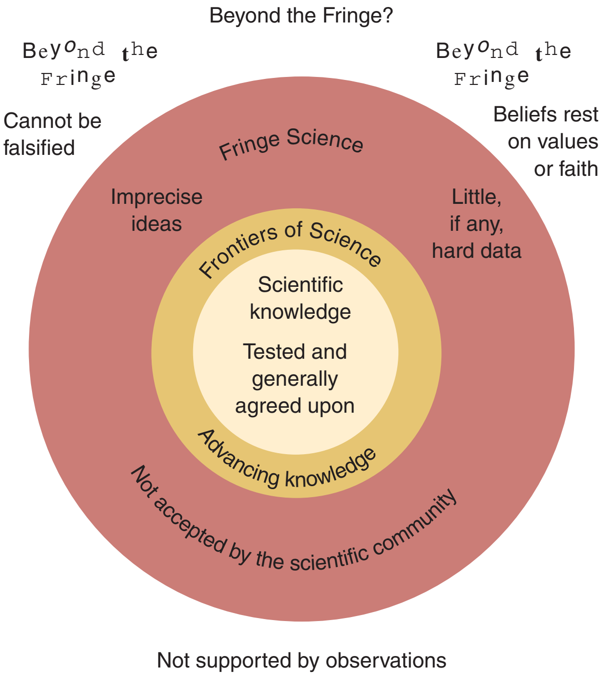

FIGURE 2.10 **Beyond the fringe? A diagrammatic view of different kinds of knowledge and ideas.**

Pseudoscientific ideas arise from various sources. With more research, however, some of the frontier ideas may move into the realm of accepted science, and new ideas will take their place at the advancing frontier (Figure 2.10).[10] Research may not support other hypotheses at the frontier, and these will be discarded. Accepted science may merge into frontier science, which in turn may merge into farther-out ideas, or fringe science. Really wild ideas may be considered beyond the fringe.

2.5 Environmental Questions and the Scientific Method

Environmental sciences deal with especially complex systems and include a relatively new set of sciences. Therefore, the process of scientific study has not always neatly followed the formal scientific method discussed earlier in this chapter. Often, observations are not used to develop formal hypotheses. Controlled laboratory experiments have been the exception rather than the rule. Much environmental research has been limited to field observations of processes and events that have been difficult to subject to controlled experiments.

Environmental research presents several obstacles to following the classic scientific method. The long time frame of many ecological processes relative to human lifetimes, professional lifetimes, and lengths of research grants poses problems for establishing statements that can in practice be subject to disproof. What do we do if a theoretical disproof through direct observation would take a century or more? Other obstacles include difficulties in setting up adequate experimental controls for field studies, in developing laboratory experiments of sufficient complexity, and in developing theory and models for complex systems. Throughout this text, we present differences between the “standard” scientific method and the actual approach that has been used in environmental sciences.

SUMMARY

- Science is one path to critical thinking about the natural world. Its goal is to gain an understanding of how nature works. Decisions on environmental issues must begin with an examination of the relevant scientific evidence. However, environmental decisions also require careful analysis of economic, social, and political consequences. Solutions will reflect religious, aesthetic, and ethical values as well.
- Science is an open-ended process of finding out about the natural world. In contrast, science lectures and texts are usually summaries of the answers arrived at through this process, and science homework and tests are exercises in finding the right answer. Therefore, students often perceive science as a body of facts to be memorized, and they view lectures and texts as authoritative sources of absolute truths about the world.
- Science begins with careful observations of the natural world, from which scientists formulate hypotheses. Whenever possible, scientists test hypotheses with controlled experiments.
- Although the scientific method is often taught as a prescribed series of steps, it is better to think of it as a general guide to scientific thinking, with many variations.
- We acquire scientific knowledge through inductive reasoning, basing general conclusions on specific observations. Conclusions arrived at through induction can never be proved with certainty. Thus, because of the inductive nature of science, it is possible to disprove hypotheses but not possible to prove them with 100% certainty.

- Measurements are approximations that may be more or less exact, depending on the measuring instruments and the people who use them. A measurement is meaningful when accompanied by an estimate of the degree of uncertainty, or error.
- Accuracy in measurement is the extent to which the measurement agrees with an accepted value. Precision is the degree of exactness with which a measurement is made. A precise measurement may not be accurate. The estimate of uncertainty provides information on the precision of a measurement.
- A general statement that relates and explains a great many hypotheses is called a theory. Theories are the greatest achievements of science.
- Critical thinking can help us distinguish science from pseudoscience. It can also help us recognize possible bias on the part of scientists and the media. Critical thinking involves questioning and synthesizing information rather than merely acquiring information.

REEXAMINING THEMES AND ISSUES

Global Perspective

The global perspective on environment arises out of new findings in environmental science.

Urban World

Our increasingly urbanized world is best understood with the assistance of scientific investigation.

People and Nature

Solutions to environmental problems require both values and knowledge. Understanding the scientific method is especially important if we are going to understand the connection between values and knowledge, and the relationship between people and nature. Ultimately, environmental decisions are policy decisions, negotiated through the political process. Policymakers often lack sufficient understanding of the scientific method, leading to false conclusions. Uncertainty is part of the nature of measurement and science. We must learn to accept uncertainty as part of our attempt to conserve and use our natural resources.

Science and Values

This chapter summarizes the scientific method, which is essential to analyzing and solving environmental problems and to developing sound approaches to sustainability.

KEY TERMS

controlled experiment	**27**
deductive reasoning	**28**
dependent variable	**26**
disprovability	**25**
experimental errors	**32**
fact	**26**
hypothesis	**26**
independent variable	**26**
inductive reasoning	**27**
inferences	**26**
manipulated variable	**26**
model	**29**
observations	**26**
operational definitions	**27**
qualitative data	**27**
quantitative data	**27**
responding variable	**27**
scientific method	**24**
scientific theory	**29**
systematic errors	**32**
variables	**27**

STUDY QUESTIONS

1. Which of the following are scientific statements and which are not? What is the basis for your decision in each case?
   (a) The amount of carbon dioxide in the atmosphere is increasing.
   (b) Condors are ugly.
   (c) Condors are endangered.
   (d) Today there are 280 condors.
   (e) Crop circles are a sign from Earth to us that we should act better.
   (f) Crop circles can be made by people.
   (g) The fate of Mono Lake is the same as the fate of the Aral Sea.

2. What is the logical conclusion of each of the following syllogisms? Which conclusions correspond to observed reality?
   (a) All men are mortal. Socrates is a man.
   Therefore______________________________
   (b) All sheep are black. Mary's lamb is white.
   Therefore______________________________
   (c) All elephants are animals. All animals are living beings.
   Therefore______________________________

3. Which of the following statements are supported by deductive reasoning and which by inductive reasoning?
   (a) The sun will rise tomorrow.
   (b) The square of the hypotenuse of a right triangle is equal to the sum of the squares of the other two sides.
   (c) Only male deer have antlers.
   (d) If $A = B$ and $B = C$, then $A = C$.
   (e) The net force acting on a body equals its mass times its acceleration.

4. The accepted value for the number of inches in a centimeter is 0.3937. Two students mark off a centimeter on a piece of paper and then measure the distance using a ruler (in inches). Student A finds the distance equal to 0.3827 in., and student B finds it equal to 0.39 in. Which measurement is more accurate? Which is more precise? If student B measured the distance as 0.3900 in., what would be your answer?

5. (a) A teacher gives five students each a metal bar and asks them to measure the length. The measurements obtained are 5.03, 4.99, 5.02, 4.96, and 5.00 cm. How can you explain the variability in the measurements? Are these systematic or random errors?
   (b) The next day, the teacher gives the students the same bars but tells them that the bars have contracted because they have been in the refrigerator. In fact, the temperature difference would be too small to have any measurable effect on the length of the bars. The students' measurements, in the same order as in part (a), are 5.01, 4.95, 5.00, 4.90, and 4.95 cm. Why are the students' measurements different from those of the day before? What does this illustrate about science?

6. Identify the independent and dependent variables in each of the following:
   (a) Change in the rate of breathing in response to exercise.
   (b) The effect of study time on grades.
   (c) The likelihood that people exposed to smoke from other people's cigarettes will contract lung cancer.

7. (a) Identify a technological advance that resulted from a scientific discovery.
   (b) Identify a scientific discovery that resulted from a technological advance.
   (c) Identify a technological device you used today. What scientific discoveries were necessary before the device could be developed?

8. What is fallacious about each of the following conclusions?
   (a) A fortune cookie contains the statement "A happy event will occur in your life." Four months later, you find a \$100 bill. You conclude that the prediction was correct.
   (b) A person claims that aliens visited Earth in prehistoric times and influenced the cultural development of humans. As evidence, the person points to ideas among many groups of people about beings who came from the sky and performed amazing feats.
   (c) A person observes that light-colored animals almost always live on light-colored surfaces, whereas dark forms of the same species live on dark surfaces. The person concludes that the light surface causes the light color of the animals.
   (d) A person knows three people who have had fewer colds since they began taking vitamin C on a regular basis. The person concludes that vitamin C prevents colds.

9. Find a newspaper article on a controversial topic. Identify some loaded words in the article—that is, words that convey an emotional reaction or a value judgment.

10. Identify some social, economic, aesthetic, and ethical issues involved in a current environmental controversy.

FURTHER READING

American Association for the Advancement of Science (AAAS), ***Science for All Americans*** (Washington, DC: AAAS, 1989). This report focuses on the knowledge, skills, and attitudes a student needs in order to be scientifically literate.

Botkin, D.B., ***No Man's Garden: Thoreau and a New Vision for Civilization and Nature*** (Washington, DC: Island Press, 2001). The author discusses how science can be applied to the study of nature and to problems associated with people and nature. He also discusses science and values.

Grinnell, F., ***The Scientific Attitude*** (New York: Guilford, 1992). The author uses examples from biomedical research to illustrate the processes of science (observing, hypothesizing, experimenting) and how scientists interact with each other and with society.

Kuhn, Thomas S., ***The Structure of Scientific Revolutions*** (Chicago: University of Chicago Press, 1996). This is a modern classic in the discussion of the scientific method, especially regarding major transitions in new sciences, such as environmental sciences.

McCain, G., and E.M. Segal, ***The Game of Science*** (Monterey, CA: Brooks/Cole, 1982). The authors present a lively look into the subculture of science.

Sagan, C., ***The Demon-Haunted World*** (New York: Random House, 1995). The author argues that irrational thinking and superstition threaten democratic institutions and discusses the importance of scientific thinking to our global civilization.