Science, Matter, Energy, and Systems

2

How Do Scientists Learn about Nature? A Story about a Forest

CORE CASE STUDY

Imagine that you learn of a logging company's plans to cut down all of the trees on a hillside in back of your house. You are very concerned and want to know the possible harmful environmental effects of this action on the hillside, the stream at bottom of the hillside, and your backyard.

One way to learn about such effects is to conduct a *controlled experiment*, just as environmental scientists do. They begin by identifying key *variables* such as water loss and soil nutrient content that might change after the trees are cut down. Then, they set up two groups. One is the *experimental group*, in which a chosen variable is changed in a known way. The other is the *control group*, in which the chosen variable is not changed. The scientists' goal is to compare the two groups after the variable has been changed and to look for differences resulting from the change.

In 1963, botanist F. Herbert Bormann, forest ecologist Gene Likens, and their colleagues began carrying out such a controlled experiment. The goal was to compare the loss of water and soil nutrients from an area of uncut forest (the *control site*) with an area that had been stripped of its trees (the *experimental site*).

They built V-shaped concrete dams across the creeks at the bottoms of several forested valleys in the Hubbard Brook Experimental Forest in New Hampshire (Figure 2-1). The dams were designed so that all surface water leaving each forested valley had to flow across a dam, where scientists could measure its volume and dissolved nutrient content.

First, the investigators measured the amounts of water and dissolved soil nutrients flowing from an undisturbed forested area in one of the valleys (the control site, Figure 2-1, left). These measurements showed that an undisturbed mature forest is very efficient at storing water and retaining chemical nutrients in its soils.

Next, they set up an experimental forest area in another of the forest's valleys (the experimental site, Figure 2-1, right). One winter, they cut down all the trees and shrubs in that valley, left them where they fell, and sprayed the area with herbicides to prevent the regrowth of vegetation. Then, for 3 years, they compared the outflow of water and nutrients in this experimental site with those in the control site.

With no plants to help absorb and retain water, the amount of water flowing out of the deforested valley increased by 30–40%. As this excess water ran rapidly over the ground, it eroded soil and carried dissolved nutrients out of the deforested site. Overall, the loss of key nutrients from the experimental forest was 6 to 8 times that in the nearby uncut control forest.

This controlled experiment revealed one of the ways in which scientists can learn about the effects of our actions on natural systems such as forests. In this chapter, you will learn more about how scientists study nature and about the matter and energy that make up the physical world within and around us. You will also learn how scientists discovered three *scientific laws*, or rules of nature, governing the changes that matter and energy undergo.

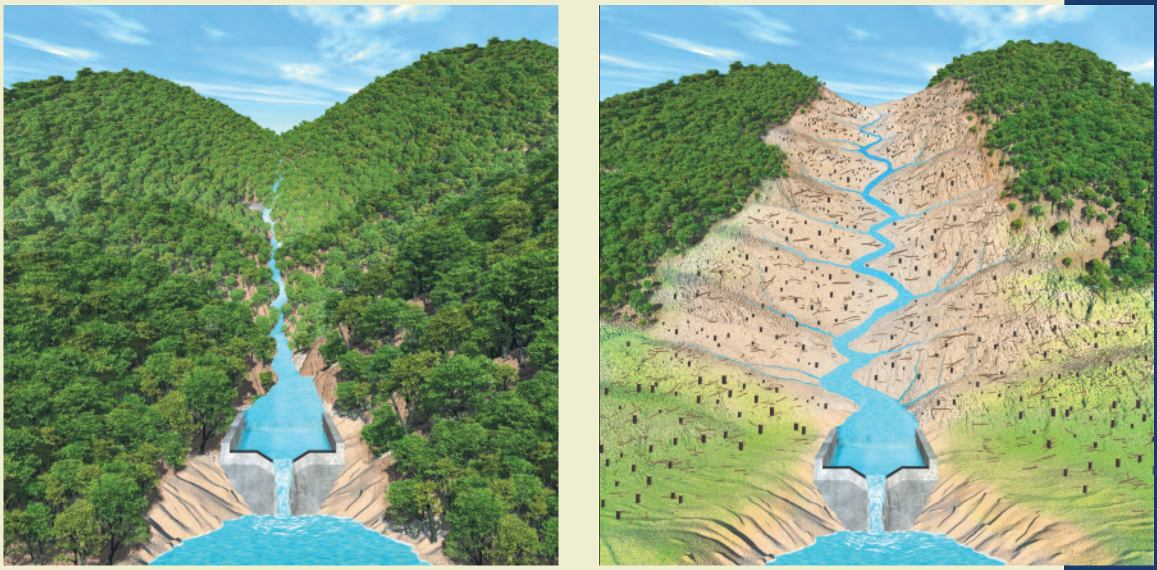


Figure 2-1 This controlled field experiment measured the effects of deforestation on the loss of water and soil nutrients from a forest. V–notched dams were built at the bottoms of two forested valleys so that all water and nutrients flowing from each valley could be collected and measured for volume and mineral content. These measurements were recorded for the forested valley (left), which acted as the control site, and for the other valley, which acted as the experimental site (right). Then all the trees in the experimental valley were cut and, for 3 years, the flows of water and soil nutrients from both valleys were measured and compared.

Key Questions and Concepts

2-1 What do scientists do?

CONCEPT 2-1 Scientists collect data and develop theories, models, and laws about how nature works.

2-2 What is matter?

CONCEPT 2-2 Matter consists of elements and compounds that are in turn made up of atoms, ions, or molecules.

2-3 What happens when matter undergoes change?

CONCEPT 2-3 Whenever matter undergoes a physical or chemical change, no atoms are created or destroyed (the law of conservation of matter).

2-4 What is energy and what happens when it undergoes change?

CONCEPT 2-4A Whenever energy is converted from one form to another in a physical or chemical change, no energy is created or destroyed (first law of thermodynamics).

CONCEPT 2-4B Whenever energy is converted from one form to another in a physical or chemical change, we end up with lower-quality or less usable energy than we started with (second law of thermodynamics).

2-5 What are systems and how do they respond to change?

CONCEPT 2-5 Systems have inputs, flows, and outputs of matter and energy, and feedback can affect their behavior.

Note: Supplements 1 (p. S2), 2 (p. S3), and 4 (p. S11) can be used with this chapter.

> *Science is built up of facts, as a house is built of stones;*
> *but an accumulation of facts is no more a science*
> *than a heap of stones is a house.*
>
> HENRI POINCARÉ

2-1 What Do Scientists Do?

▶ **CONCEPT 2-1 Scientists collect data and develop theories, models, and laws about how nature works.**

Science Is a Search for Order in Nature

Science is a human effort to discover how the physical world works by making observations and measurements, and carrying out experiments. It is based on the assumption that events in the physical world follow orderly cause-and-effect patterns that we can understand.

You may have heard that scientists follow a specific set of steps called the *scientific method* to learn about how the physical world works. In fact, they use a variety of methods to study nature, although these methods tend to fall within a general process described in Figure 2-2.

There is nothing mysterious about this process. You use it all the time in making decisions, as shown in Figure 2-3. As the famous physicist Albert Einstein put it, "The whole of science is nothing more than a refinement of everyday thinking."

Scientists Use Observations, Experiments, and Models to Answer Questions about How Nature Works

Here is a more formal outline of the steps scientists often take in trying to understand the natural world, although they do not always follow the steps in the order listed. This outline is based on the scientific experiment carried out by Bormann and Likens (**Core Case Study**), which illustrates the nature of the scientific process shown in Figure 2-2.

- *Identify a problem*. Bormann and Likens identified the loss of water and soil nutrients from cutover forests as a problem worth studying.
- *Find out what is known about the problem*. Bormann and Likens searched the scientific literature to find out what scientists knew about both the retention and the loss of water and soil nutrients in forests.

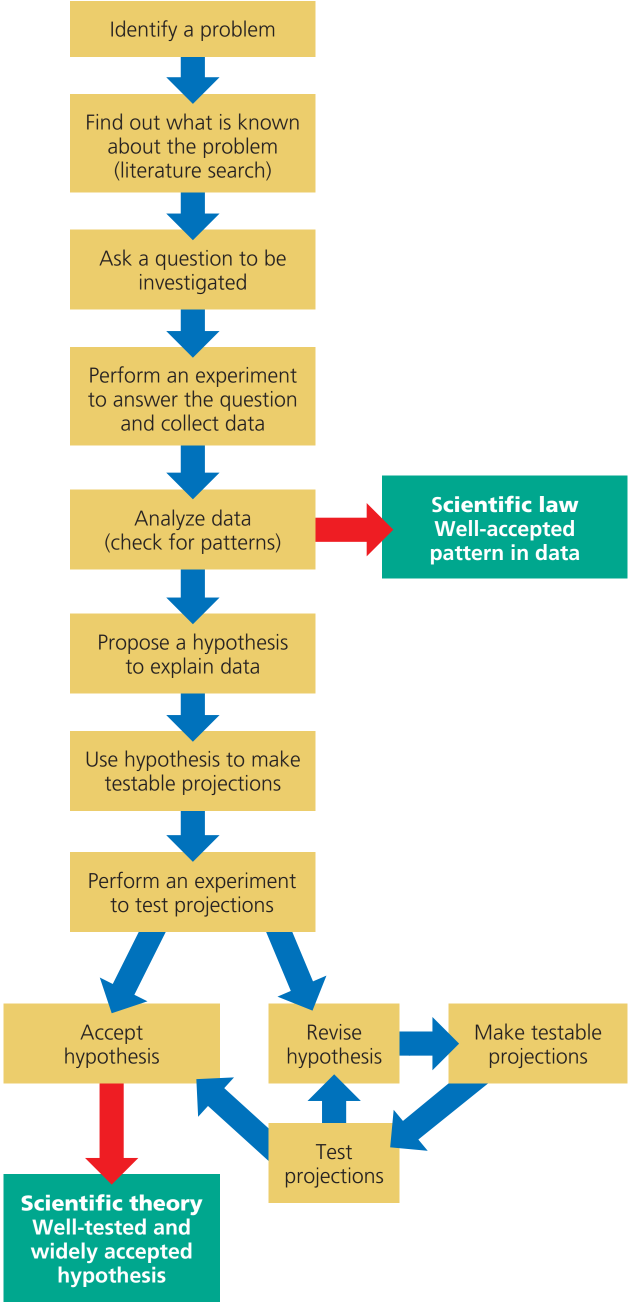


Figure 2-2 This diagram illustrates what scientists do. Scientists use this overall process for testing ideas about how the natural world works. However, they do not necessarily follow the order of steps shown here. For example, sometimes a scientist might start by coming up with a hypothesis to answer the initial question and then run experiments to test the hypothesis.

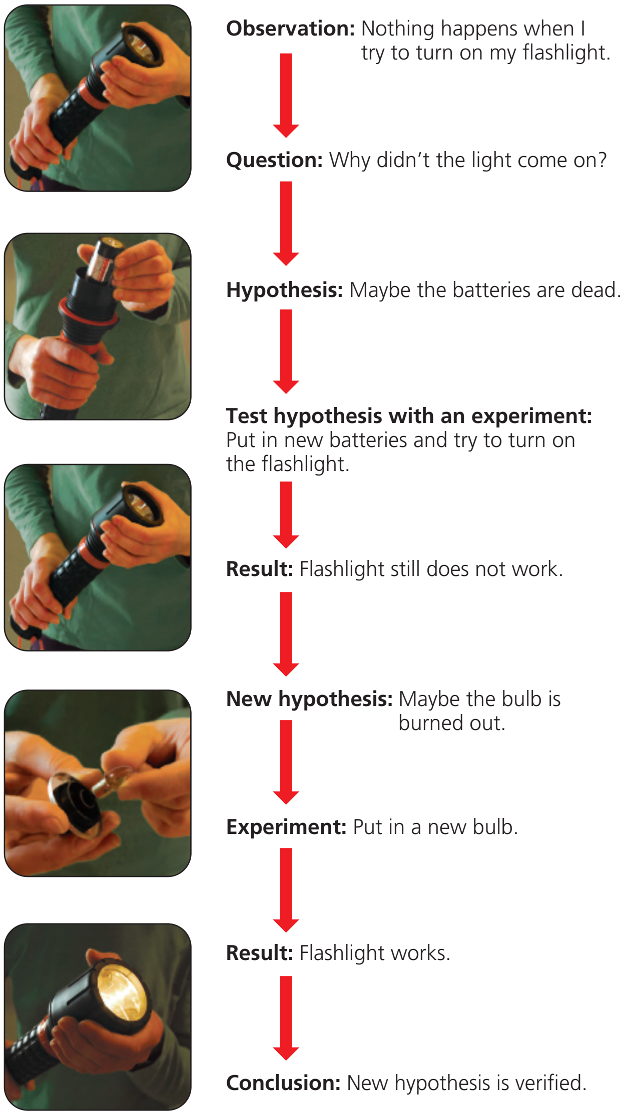


Figure 2-3 We can use the scientific process to understand and deal with an everyday problem.

- *Ask a question to investigate*. The scientists asked: "How does clearing forested land affect its ability to store water and retain soil nutrients?"
- *Collect data to answer the question*. To collect **data**—information needed to answer their questions—scientists make observations and measurements. Bormann and Likens collected and analyzed data on the water and soil nutrients flowing from a valley with an undisturbed forest (Figure 2-1, left) and from a nearby valley where they had cleared the forest for their experiment (Figure 2-1, right).
- *Propose a hypothesis to explain the data*. Scientists suggest a **scientific hypothesis**—a possible explanation of what scientists observe in nature or in the results of their experiments. The data collected by Bormann and Likens showed that clearing a forest decreases its ability to store water and retain soil nutrients such as nitrogen. They came up with the following hypothesis to explain their data: When a forest is cleared of its vegetation and exposed to rain and melting snow, it retains less water than it did before it was cleared and loses large quantities of its soil nutrients.
- *Make testable projections*. Scientists make projections about what should happen if their hypothesis is valid and then run experiments to test the projections. Bormann and Likens projected that if their hypothesis was valid for nitrogen, then a cleared forest should also lose other soil nutrients such as

phosphorus over a similar time period and under similar weather conditions.

- *Test the projections with further experiments, models, or observations*. To test their projection, Bormann and Likens repeated their controlled experiment and measured the phosphorus content of the soil. Another way to test projections is to develop a **model**, an approximate representation or simulation of a system, in this case a deforested valley, being studied. Data from the research carried out by Bormann and Likens and from other scientists' research can be fed into such models and used to project the loss of phosphorus and other types of soil nutrients. Scientists can then compare these projections with the actual measured losses to test the validity of the models.
- *Accept or reject the hypothesis*. If their new data do not support their hypothesis, scientists come up with other testable explanations. This process of proposing and testing various hypotheses goes on until there is general agreement among the scientists in this field of study that a particular hypothesis is the best explanation of the data. After Bormann and Likens confirmed that the soil in a cleared forest also loses phosphorus, they measured losses of other soil nutrients, which further supported their hypothesis. Research and models by other scientists also supported the hypothesis. A well-tested and widely accepted scientific hypothesis or a group of related hypotheses is called a **scientific theory**. Thus, Bormann and Likens and other scientists developed a theory that trees and other plants hold soil in place and help it to retain water and nutrients needed by the plants for their growth.

Scientists Are Curious and Skeptical, and Demand Lots of Evidence

Four important features of the scientific process are *curiosity, skepticism, reproducibility,* and *peer review.* Good scientists are extremely curious about how nature works. But they tend to be highly skeptical of new data, hypotheses, and models until they can test and verify them with lots of evidence. Scientists say, "Show me your evidence and explain the reasoning behind the scientific ideas or hypotheses that you propose to explain your data." They also require that any evidence gathered must be reproducible. In other words, other scientists should be able to get the same results when they run the same experiments.

Science is a community effort, and an important part of the scientific process is **peer review**. It involves scientists openly publishing details of the methods and models they used, the results of their experiments, and the reasoning behind their hypotheses for other scientists working in the same field (their peers) to evaluate.

CORE CASE STUDY

For example, Bormann and Likens (**Core Case Study**) submitted the results of their forest experiments to a respected scientific journal. Before publishing this report, the journal's editors asked other soil and forest experts to review it. Other scientists have repeated the measurements of soil content in undisturbed and cleared forests of the same type and also for different types of forests. Their results have been subjected to peer review as well. In addition, computer models of forest systems have been used to evaluate this problem, with the results also subjected to peer review.

Scientific knowledge advances in this self-correcting way, with scientists continually questioning the measurements and data produced by their peers. They also collect new data and sometimes come up with new and better hypotheses (Science Focus, p. 35). Skepticism and debate among peers in the scientific community is essential to the scientific process—explaining why science is sometimes described as organized skepticism.

Critical Thinking and Creativity Are Important in Science

Scientists use logical reasoning and critical thinking skills (p. 2) to learn about the natural world. Such skills help scientists and the rest of us to distinguish between facts and opinions, evaluate evidence and arguments, and develop informed positions on issues.

Thinking critically involves three important steps:

1. Be skeptical about everything we read or hear.
2. Look at the evidence to evaluate it and any related information and opinions that may come from various sources. Validating information is especially important in the Internet age where we can be exposed to unreliable data, some of which may be just opinions from uninformed amateurs posing as experts.
3. Identify and evaluate our personal assumptions, biases, and beliefs. As the American psychologist and philosopher William James observed, "A great many people think they are thinking when they are merely rearranging their prejudices." We can also heed the words of the American writer Mark Twain: "It's what we know is true, but just ain't so, that hurts us."

Logic and critical thinking are very important tools in science, but imagination, creativity, and intuition are just as vital. According to physicist Albert Einstein, "There is no completely logical way to a new scientific idea." Most major scientific advances are made by creative people who come up with new and better ways to help us understand how the natural world works. As American educator John Dewey remarked, "Every great advance in science has issued from a new audacity of imagination."

SCIENCE FOCUS

Easter Island: Some Revisions in a Popular Environmental Story

For years, the story of Easter Island has been used in textbooks as an example of how humans can seriously degrade their own life-support system. It concerns a civilization that once thrived and then largely disappeared from a small, isolated island located about 3,600 kilometers (2,200 miles) off the coast of Chile in the great expanse of the South Pacific.

Scientists used anthropological evidence and scientific measurements to estimate the ages of some of the more than 300 large statues (Figure 2-A) found on Easter Island. They hypothesized that about 2,900 years ago, Polynesians used double-hulled, seagoing canoes to colonize the island. The settlers probably found a paradise with fertile soil that supported dense and diverse forests and lush grasses. According to this hypothesis, the islanders thrived, and their population increased to as many as 15,000 people.

Measurements made by scientists seemed to indicate that over time, the Polynesians began living unsustainably by using the island's forest and soil resources faster than they could be renewed. They cut down trees and used them for firewood, for building seagoing canoes, and for moving and erecting the gigantic statues. Once they had used up the large trees, the islanders could no longer build their traditional seagoing canoes for fishing in deeper offshore waters, and no one could escape the island by boat.

It was hypothesized that without the once-great forests to absorb and slowly release water, springs and streams dried up, exposed soils were eroded, crop yields plummeted, and famine struck. There was no firewood for cooking or keeping warm. According to the original hypothesis, the population and the civilization collapsed as rival clans fought one another for dwindling food supplies, and the island's population dropped sharply. By the late 1870s, only about 100 native islanders were left.

In 2006, anthropologist Terry L. Hunt, Director of the University of Hawaii Rapa Nui (Easter Island) Archaeological Field School at the University of Hawaii, evaluated the accuracy of past measurements and other evidence and carried out new measurements to estimate the ages of various statues and other artifacts. He used these data to formulate an alternative hypothesis describing the human tragedy on Easter Island.

Figure 2-A These and many other massive stone figures once lined the coasts of Easter Island and are the remains of the technology created on the island by an ancient civilization of Polynesians. Some of these statues are taller than an average five-story building and can weigh as much as 89 metric tons (98 tons).

modestlife/Shutterstock

Hunt used the data he gathered to come to several new conclusions. *First*, the Polynesians arrived on the island about 800 years ago, not 2,900 years ago. *Second*, their population size probably never exceeded 3,000, contrary to the earlier estimate of up to 15,000. *Third*, the Polynesians did use the island's trees and other vegetation in an unsustainable manner, and by 1722, visitors reported that most of the island's trees were gone.

But one question not answered by the earlier hypothesis was, why did the trees never grow back? Recent evidence and Hunt's new hypothesis suggest that rats (which either came along with the original settlers as stowaways or were brought along as a source of protein for the long voyage) played a key role in the island's permanent deforestation. Over the years, the rats multiplied rapidly into the millions and devoured the seeds that would have regenerated the forests.

Another of Hunt's conclusions was that after 1722, the population of Polynesians on the island dropped to about 100, mostly from contact with European visitors and invaders. Hunt hypothesized that these newcomers introduced fatal diseases, killed off some of the islanders, and took large numbers of them away to be sold as slaves.

This story is an excellent example of how science works. The gathering of new scientific data and the reevaluation of older data led to a revised hypothesis that challenges earlier thinking about the decline of civilization on Easter Island. As a result, the tragedy may not be as clear an example of human-caused ecological collapse as was once thought.

Critical Thinking

Does the new doubt about the original Easter Island hypothesis mean that we should not be concerned about using resources unsustainably on the island in space that we call earth? Explain.

Scientific Theories and Laws Are the Most Important and Certain Results of Science

Facts and data are essential to science, but its real goal is to develop theories and laws, based on facts, that explain how the physical world works, as illustrated in the quotation that opens this chapter.

When an overwhelming body of observations and measurements supports a scientific hypothesis or group of related hypotheses, it becomes a scientific theory. *We should never take a scientific theory lightly.* It has been tested widely, is supported by extensive evidence, and is accepted as being a useful explanation by most scientists in a particular field or related fields of study.

Because of this rigorous testing process, scientific theories are rarely overturned unless new evidence discredits them or scientists come up with better explanations. So when you hear someone say, “Oh, that’s just a theory,” you will know that he or she does not have a clear understanding of what a scientific theory is, how important it is, and how rigorously it has been tested before reaching this level of acceptance. In sports terms, developing a widely accepted scientific theory is roughly equivalent to winning a gold medal in the Olympics.

Another important and reliable outcome of science is a **scientific law**, or **law of nature**—a well-tested and widely accepted description of what we find happening repeatedly in nature in the same way. An example is the *law of gravity*. After making many thousands of observations and measurements of objects falling from different heights, scientists developed the following scientific law: all objects fall to the earth’s surface at predictable speeds.

We can break a society’s law, for example, by driving faster than the speed limit. But *we cannot break a scientific* law, unless we discover new data that lead to changes in the law.

For a superb look at how the scientific process is applied to expanding our understanding of the natural world, see the Annenberg Video series, *The Habitable Planet: A Systems Approach to Environmental Science* (see the website at **www.learner.org/resources/series209.html**). Each of the 13 videos describes how scientists working on two different problems related to each subject are learning about how nature works. We regularly cross-reference material in this book to these videos.

The Results of Science Can Be Tentative, Reliable, or Unreliable

A fundamental part of science is *testing*. Scientists insist on testing their hypotheses, models, methods, and results over and over again. In this way, they seek to establish the reliability of these scientific tools and the resulting conclusions that they reveal about how some part of the physical world works.

Sometimes, preliminary scientific results that capture news headlines are controversial because they have not been widely tested and accepted by peer review. They are not yet considered reliable, and can be thought of as **tentative science** or **frontier science**. Some of these results will be validated and classified as reliable and some will be discredited and classified as unreliable. At the frontier stage, it is normal for scientists to disagree about the meaning and accuracy of data and the validity of hypotheses and results. This is how scientific knowledge advances. But unless critics can come up with new and better data and better hypotheses, their dissent becomes unproductive. At that point, most scientists in a particular field stop listening to them and move on.

By contrast, **reliable science** consists of data, hypotheses, models, theories, and laws that are widely accepted by all or most of the scientists who are considered experts in the field under study, in what is referred to as a *scientific consensus*. The results of reliable science are based on the self-correcting process of testing, open peer review, reproducibility, and debate. New evidence and better hypotheses may discredit or alter accepted views. But until that happens, those views are considered to be the results of reliable science. **Explore More:** See a Science Focus at **www.cengage.com/login** to learn about the 30-year debate over, and development of, a scientific consensus on atmospheric warming.

Scientific hypotheses and results that are presented as reliable without having undergone the rigors of widespread peer review, or that have been discarded as a result of peer review, are considered to be **unreliable science**. Here are some critical thinking questions you can use to uncover unreliable science:

- Was the experiment well designed? Did it involve a control group? (**Core Case Study**) CORE CASE STUDY
- Have other scientists reproduced the results?
- Does the proposed hypothesis explain the data? Have scientists made and verified projections based on the hypothesis?
- Are there no other, more reasonable explanations of the data?
- Are the investigators unbiased in their interpretations of the results? Was all of their funding from unbiased sources?
- Have the data and conclusions been subjected to peer review?
- Are the conclusions of the research widely accepted by other experts in this field?

If “yes” is the answer to each of these questions, then you can classify the results as reliable science. Otherwise, the results may represent tentative science that needs further testing and evaluation, or you can classify them as unreliable science.

Science Has Some Limitations

Environmental science and science in general have five important limitations. *First*, scientists cannot prove or disprove anything absolutely, because there is always some degree of uncertainty in scientific measurements, observations, and models. Instead, scientists try to establish that a particular scientific theory or law has a very high *probability* or *certainty* (at least 90%) of being useful for understanding some aspect of nature. Many scientists don’t use the word *proof* because this implies “absolute proof” to people who don’t understand how science works. For example, most scientists will rarely say something like, “Cigarettes cause lung cancer.” Rather, they might say, “Overwhelming evidence from thousands of studies indicates that people who smoke have a greatly increased chance of developing lung cancer.”

Suppose someone tells you that some statement is not true because it has not been scientifically proven. When this happens, you can draw one of two conclusions:

1. The individual does not understand how science works, because while scientists can establish a very high degree of certainty (more than 90%) that a scientific theory is useful in explaining something about how nature works, they can never prove or disprove anything absolutely.
2. The individual is using an old debating trick to influence your thinking by telling you something that is true but irrelevant and misleading.

THINKING ABOUT
Scientific Proof

Does the fact that science can never prove anything absolutely mean that its results are not valid or useful? Explain.

A *second* limitation of science is that scientists are human and thus are not totally free of bias about their own results and hypotheses. However, the high standards of evidence required through peer review can usually uncover or greatly reduce personal bias and expose occasional cheating by scientists who falsify their results.

A *third* limitation—especially important to environmental science—is that many systems in the natural world involve a huge number of variables with complex interactions. This makes it difficult and too costly to test one variable at a time in controlled experiments such as the one described in the **Core Case Study** that opens this chapter. To try to deal with this problem, scientists develop *mathematical models* that can take into account the interactions of many variables. Running such models on high-speed computers can sometimes overcome the limitations of testing each variable individually, saving both time and money. In addition, scientists can use computer models to simulate global experiments on phenomena like climate change that are impossible to do in a controlled physical experiment.

A *fourth* limitation of science involves the use of statistical tools. For example, there is no way to measure accurately how many metric tons of soil are eroded annually worldwide. Instead, scientists use statistical sampling and other mathematical methods to estimate such numbers (Science Focus, below). However, such results should not be dismissed as “only estimates” because they can indicate important trends.

SCIENCE FOCUS

Statistics and Probability

Statistics consists of mathematical tools that we can use to collect, organize, and interpret numerical data. For example, suppose we make measurements of the weight of each individual in a population of 15 rabbits. We can use statistics to calculate the *average* weight of the population. To do this we add up the combined weights of the 15 rabbits and divide the total by 15. In another example, Bormann and Likens (**Core Case Study**) made many measurements of nitrate levels in the water flowing from their undisturbed and deforested valleys (Figure 2-1) and then averaged the results to get the most reliable value.

Scientists also use the statistical concept of probability to evaluate their results. **Probability** is the chance that something will happen or will be valid. For example, if you toss a nickel, what is the chance that it will come up heads? If your answer is 50%, you are correct. The probability of the nickel coming up heads is 1/2, which can also be expressed as 50% or 0.5. Probability is often expressed as a number between 0 and 1 written as a decimal (such as 0.5).

Now suppose you toss the coin ten times and it comes up heads six times. Does this mean that the probability of it coming up heads is 0.6 or 60%? The answer is no because the *sample size*—the number of objects or events studied—was too small to yield a statistically accurate result. If you increase your sample size to 1,000 by tossing the coin 1,000 times, you are almost certain to get heads 50% of the time and tails 50% of the time.

In addition to having a large enough sample size, it is also important when doing scientific research in a physical area to take samples from different places, in order to get a reasonable evaluation of the variable you are studying. For example, if you wanted to study the effects of a certain air pollutant on the needles of a pine tree species, you would need to locate different stands of the species that are exposed to the pollutant over a certain period of time. At each location, you would need to make measurements of the atmospheric levels of the pollutant at different times and average the results. You would also need to take measurements of the damage (such as needle loss) from a large enough number of trees in each location over the same time period. Then you would average the results in each location and compare the results among all locations.

If the average results were consistent in different locations, you could then say that there is a certain probability, say 60% (or 0.6), that this type of pine tree suffered a certain percentage loss of its needles when exposed to a specified average level of the pollutant over a given time. You would also need to run further experiments to determine that other factors, such as natural needle loss, extreme temperatures, insects, plant diseases, and drought did not cause the needle losses you observed. As you can see, obtaining reliable scientific results is not a simple process.

Critical Thinking

What does it mean when an international body of the world’s climate experts says that there is at least a 90% chance (probability of 0.9) that human activities, primarily the burning of fossil fuels and the resulting carbon dioxide emissions, have been an important cause of the observed atmospheric warming during the past 35 years? Why is it that we would probably never see a 100% chance?

Finally, the scientific process is limited to understanding the natural world. It cannot be applied to moral or ethical questions because such questions are about matters for which scientists cannot collect data from the natural world. For example, scientists can use the scientific process to understand the effects of removing trees from an ecosystem, but this process does not tell them whether it is morally or ethically right or wrong to remove the trees.

Despite these five limitations, science is the most useful way that we have for learning about how nature works and projecting how it might behave in the future. With this important set of tools, we have made significant progress, but we still know too little about how the earth works, its present state of environmental health, and the current and future environmental impacts of our activities. These knowledge gaps point to important *research frontiers*, several of which are highlighted throughout this text.

GOOD NEWS

2-2 What Is Matter?

▶ **CONCEPT 2-2 Matter consists of elements and compounds that are in turn made up of atoms, ions, or molecules.**

Matter Consists of Elements and Compounds

To begin our study of environmental science, we look at matter—the stuff that makes up life and its environment. **Matter** is anything that has mass and takes up space. It can exist in three *physical states*—solid, liquid, and gas. Water, for example, exists as solid ice, liquid water, or water vapor depending mostly on its temperature.

Matter also exists in two *chemical forms*—elements and compounds. An **element** is a fundamental type of matter that has a unique set of properties and cannot be broken down into simpler substances by chemical means. For example, the elements gold (Figure 2-4, left), and mercury (Figure 2-4, right) cannot be broken down chemically into any other substance.

Some matter is composed of one element, such as gold or mercury (Figure 2-4). But most matter consists of **compounds**, combinations of two or more different elements held together in fixed proportions. For example, water is a compound made of the elements hydrogen and oxygen that combine chemically with one another. (See Supplement 4 on p. S11 for an expanded discussion of basic chemistry.)

To simplify things, chemists represent each element by a one- or two-letter symbol. Table 2-1 lists the elements and their symbols that you need to know to understand the material in this book.

Table 2-1 Chemical Elements Used in This Book

Element	Symbol
Arsenic	As
Bromine	Br
Calcium	Ca
Carbon	C
Chlorine	Cl
Fluorine	F
Gold	Au
Lead	Pb
Lithium	Li
Mercury	Hg
Nitrogen	N
Phosphorus	P
Sodium	Na
Sulfur	S
Uranium	U

Morgan Lane Photography/Shutterstock

Andraž Cerar/Shutterstock

Figure 2-4 Gold (left) and mercury (right) are chemical elements; each has a unique set of properties and it cannot be broken down into simpler substances.

Atoms, Molecules, and Ions Are the Building Blocks of Matter

The most basic building block of matter is an **atom**, the smallest unit of matter into which an element can be divided and still have its characteristic chemical properties. The idea that all elements are made up of atoms is called the **atomic theory** and it is the most widely accepted scientific theory in chemistry.

Atoms are incredibly small. In fact, more than 3 million hydrogen atoms could sit side by side on the period at the end of this sentence.

CONNECTIONS

How Much Is a Million? A Billion? A Trillion?

Numbers such as millions, billions, and trillions are widely used but are often hard to comprehend. Here are a couple of ways to think about them. If you were to start counting, one number per second, and keep going 24 hours a day, it would take you 12 days (with no breaks) to get to a million. It would take you 32 years to get to a billion. And you would have to count for 32,000 years to reach a trillion. If you got paid for your efforts at a dollar per number and you stacked the bills (each set of five one-dollar bills being one millimeter high), your first million dollar bills would be 20 meters (66 feet) high—higher than a 3-story building. A stack of a billion dollar bills would reach a height of 200 kilometers (124 miles), or nearly the distance between Pittsburgh, Pennsylvania and Cleveland, Ohio (USA). A stack of a trillion dollar bills would reach about 200,000 kilometers (124,200 miles), which is more than halfway to the moon.

Atoms have an internal structure. If you could view them with a supermicroscope, you would find that each different type of atom contains a certain number of three types of *subatomic particles*: **neutrons (n)** with no electrical charge, **protons (p)** with a positive electrical charge (+), and **electrons (e)** with a negative electrical charge (−).

Each atom consists of an extremely small center called the **nucleus**—containing one or more protons and, in most cases, one or more neutrons—and one or more electrons in rapid motion somewhere around the nucleus (Figure 2-5). Each atom has equal numbers of positively charged protons and negatively charged electrons. Because these electrical charges cancel one another, *atoms as a whole have no net electrical charge.*

Each element has a unique **atomic number** equal to the number of protons in the nucleus of its atom. Carbon (C), with 6 protons in its nucleus (Figure 2-5), has an atomic number of 6, whereas uranium (U), a much larger atom, has 92 protons in its nucleus and an atomic number of 92.

Because electrons have so little mass compared to protons and neutrons, *most of an atom's mass is concentrated in its nucleus.* The mass of an atom is described by its **mass number**, the total number of neutrons and protons in its nucleus. For example, a carbon atom with 6 protons and 6 neutrons in its nucleus has a mass number of 12, and a uranium atom with 92 protons and 143 neutrons in its nucleus has a mass number of 235 (92 + 143 = 235).

Each atom of a particular element has the same number of protons in its nucleus. But the nuclei of atoms of a particular element can vary in the number of neutrons they contain, and therefore, in their mass numbers. The forms of an element having the same atomic number but different mass numbers are called **isotopes** of that element. Scientists identify isotopes by attaching their mass numbers to the name or symbol of the element. For example, the three most common isotopes of carbon are carbon-12 (Figure 2-5, with six protons and six neutrons), carbon-13 (with six protons and seven neutrons), and carbon-14 (with six protons and eight neutrons). Carbon-12 makes up about 98.9% of all naturally occurring carbon.

A second building block of matter is a **molecule**, a combination of two or more atoms of the same or different elements held together by forces called *chemical bonds*. Molecules are the basic building blocks of many compounds. Examples of molecules are water, or H_2O, which consists of two atoms of hydrogen and one atom of oxygen held together by chemical bonds. Another example is methane, or CH_4 (the major component of natural gas), which consists of four atoms of hydrogen and one atom of carbon. (See Figure 4 on p. S12 in Supplement 4 for other examples of molecules.)

A third building block of some types of matter is an **ion**—an atom or a group of atoms with one or more net positive or negative electrical charges. Like atoms, ions are made up of protons, neutrons, and electrons. A positive ion forms when an atom loses one or more of its negatively charged electrons, and a negative ion forms when an atom gains one or more negatively charged electrons. (See p. S12 in Supplement 4 for more details on how ions form.)

Chemists use a superscript after the symbol of an ion to indicate how many positive or negative electrical charges it has, as shown in Table 2-2 (p. 40). (One positive or negative charge is designated by a plus sign or a

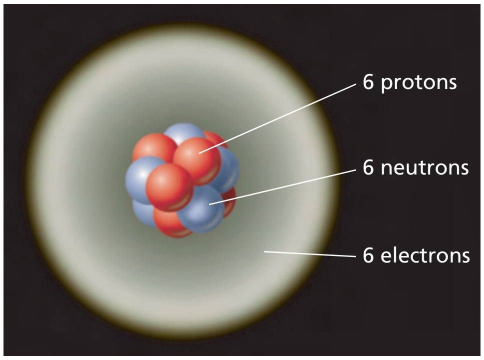


Figure 2-5 This is a greatly simplified model of a carbon-12 atom. It consists of a nucleus containing six protons, each with a positive electrical charge, and six neutrons with no electrical charge. Six negatively charged electrons are found outside its nucleus. We cannot determine the exact locations of the electrons. Instead, we can estimate the *probability* that they will be found at various locations outside the nucleus—sometimes called an *electron probability cloud*. This is somewhat like saying that there are six airplanes flying around inside a cloud. We do not know their exact location, but the cloud represents an area in which we can probably find them.

Table 2-2 Chemical Ions Used in This Book

Positive Ion	Symbol	Components
hydrogen ion	H^+	One H atom, one positive charge
sodium ion	Na^+	One Na atom, one positive charge
calcium ion	Ca^{2+}	One Ca atom, two positive charges
aluminum ion	Al^{3+}	One Al atom, three positive charges
ammonium ion	NH_4^+	One N atom, four H atoms, one positive charge
Negative Ion	**Symbol**	**Components**
chloride ion	Cl^-	One chlorine atom, one negative charge
hydroxide ion	OH^-	One oxygen atom, one hydrogen atom, one negative charge
nitrate ion	NO_3^-	One nitrogen atom, three oxygen atoms, one negative charge
carbonate ion	CO_3^{2-}	One carbon atom, three oxygen atoms, two negative charges
sulfate ion	SO_4^{2-}	One sulfur atom, four oxygen atoms, two negative charges
phosphate ion	PO_4^{3-}	One phosphorus atom, four oxygen atoms, three negative charges

minus sign, respectively.) Note in the table that some ions are forms of one element, like hydrogen (H^+), and some are combinations of more than one, such as oxygen and hydrogen (OH^-).

One example of the importance of ions in our study of environmental science is the nitrate ion (NO_3^-), a nutrient essential for plant growth. Figure 2-6 shows measurements of the loss of nitrate ions from the deforested area (Figure 2-1, right) in the controlled experiment run by Bormann and Likens (**Core Case Study**). Numerous chemical analyses of the water flowing through the dam at the cleared forest site showed an average 60-fold rise in the concentration of NO_3^- compared to water running off the forested site. After a few years, however, vegetation began growing back on the cleared valley and nitrate levels in its runoff returned to normal levels.

Ions are also important for measuring a substance's **acidity** in a water solution, a chemical characteristic that helps determine how a substance dissolved in water will interact with and affect its environment. The acidity of a water solution is based on the comparative amounts of hydrogen ions (H^+) and hydroxide ions (OH^-) contained in a particular volume of the solution. Scientists use **pH** as a measure of acidity. Pure water (not tap water or rainwater) has an equal number of H^+ and OH^- ions. It is called a neutral solution and has a pH of 7. An *acidic solution* has more hydrogen ions than hydroxide ions and has a pH less than 7. A *basic solution* has more hydroxide ions than hydrogen ions and has a pH greater than 7. (See Figure 5, p. S13, in Supplement 4 for more details.)

Chemists use a **chemical formula** to show the number of each type of atom or ion in a compound. This shorthand contains the symbol for each element present (Table 2-1) and uses subscripts to show the number of atoms or ions of each element in the compound's basic structural unit. For example, water is a *molecular compound* that is made up of H_2O molecules. Sodium chloride (NaCl) is an *ionic compound* that is made up of a regular network of positively charged sodium ions (Na^+) and negatively charged chloride ions (Cl^-), (as shown in Figure 2 on p. S12 of Supplement 4). These and other compounds important to our study of environmental science are listed in Table 2-3.

You might want to mark these pages containing Tables 2-1, 2-2, and 2-3, because they show the key elements, ions, and compounds used in this book. Think

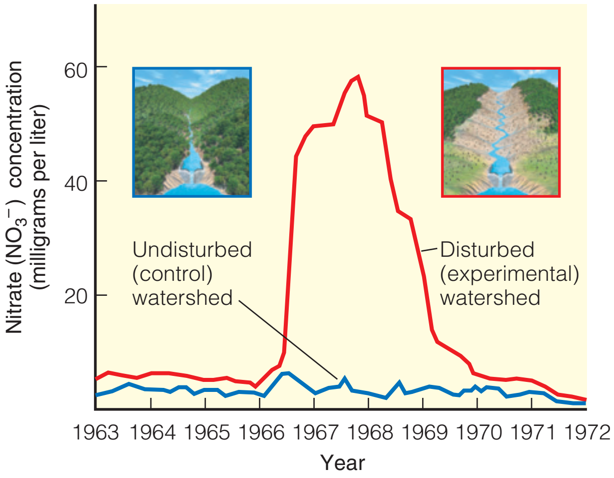


Figure 2-6 This graph shows the loss of nitrate ions (NO_3^-) from a deforested watershed in the Hubbard Brook Experimental Forest (Figure 2-1, right). The average concentration of nitrate ions in runoff from the experimental deforested watershed was about 60 times greater than in a nearby unlogged watershed used as a control (Figure 2-1, left). (Data from F. H. Bormann and Gene Likens)

Table 2-3 Compounds Used in This Book

Compound	Formula
sodium chloride	NaCl
sodium hydroxide	NaOH
carbon monoxide	CO
oxygen	O_2
nitrogen	N_2
chlorine	Cl_2
carbon dioxide	CO_2
nitric oxide	NO
nitrogen dioxide	NO_2
nitrous oxide	N_2O
nitric acid	HNO_3
methane	CH_4
glucose	$C_6H_{12}O_6$
water	H_2O
hydrogen sulfide	H_2S
sulfur dioxide	SO_2
sulfuric acid	H_2SO_4
ammonia	NH_3
calcium carbonate	$CaCO_3$

of them as lists of the main chemical characters in the story of matter that makes up the natural world.

CENGAGE**NOW**™ Examine atoms—their parts, how they work, and how they bond together to form molecules—at CengageNOW.

Organic Compounds Are the Chemicals of Life

Plastics, as well as table sugar, vitamins, aspirin, penicillin, and most of the chemicals in your body are called **organic compounds** because they contain at least two carbon atoms combined with atoms of one or more other elements. All other compounds are called **inorganic compounds**. One exception, methane (CH_4), has only one carbon atom but is considered an organic compound.

The millions of known organic (carbon-based) compounds include the following:

- *Hydrocarbons*: compounds of carbon and hydrogen atoms. One example is methane (CH_4), the main component of natural gas, and the simplest organic compound. Another is octane (C_8H_{18}), a major component of gasoline.
- *Chlorinated hydrocarbons*: compounds of carbon, hydrogen, and chlorine atoms. An example is the insecticide DDT ($C_{14}H_9Cl_5$).
- *Simple carbohydrates (simple sugars)*: certain types of compounds of carbon, hydrogen, and oxygen atoms. An example is glucose ($C_6H_{12}O_6$), which most plants and animals break down in their cells to obtain energy. (For more details, see Figure 7 on p. S14 in Supplement 4.)

Larger and more complex organic compounds, essential to life, are composed of *macromolecules*. Some of these molecules are called *polymers*, formed when a number of simple organic molecules (*monomers)* are linked together by chemical bonds—somewhat like rail cars linked in a freight train. The three major types of organic polymers are

- *Complex carbohydrates* such as cellulose and starch, which consist of two or more monomers of simple sugars such as glucose (see Figure 7, p. S14, in Supplement 4),
- *Proteins* formed by monomers called *amino acids* (see Figure 8, p. S14, in Supplement 4), and
- *Nucleic acids* (DNA and RNA) formed by monomers called *nucleotides* (see Figures 9 and 10, pp. S14 and S15, in Supplement 4).

Lipids, which include fats and waxes, are not made of monomers but are a fourth type of macromolecule essential for life (see Figure 11, p. S15, in Supplement 4).

Matter Comes to Life through Genes, Chromosomes, and Cells

The story of matter, starting with the hydrogen atom, becomes more complex as molecules grow in complexity. This is no less true when we examine the fundamental components of life. The bridge between nonliving and living matter lies somewhere between large molecules and **cells**—the fundamental structural and functional units of life.

All organisms are composed of cells. They are minute compartments covered with a thin membrane, and within them, the processes of life occur. The idea that all living things are composed of cells is called the *cell theory* and it is the most widely accepted scientific theory in biology.

Above, we mentioned nucleotides in DNA (see Figures 9 and 10, pp. S14 and S15, in Supplement 4). Within some DNA molecules are certain sequences of nucleotides called **genes**. Each of these distinct pieces of DNA contains instructions, or codes, called *genetic information*, for making specific proteins. Each of these coded units of genetic information leads to a specific **trait**, or characteristic, passed on from parents to offspring during reproduction in an animal or plant.

In turn, thousands of genes make up a single **chromosome**, a double helix DNA molecule (see Figure 10, p. S15, in Supplement 4) wrapped around some proteins. Humans have 46 chromosomes, mosquitoes have 8, and a fish known as a carp has 104. Genetic information coded in your chromosomal DNA is what makes you different from an oak leaf, an alligator, or a mosquito, and from your parents. In other words, it makes you human, but it also makes you unique. The relationships among genetic material and cells are depicted in Figure 2-7, p. 42).

Some Forms of Matter Are More Useful than Others

Matter quality is a measure of how useful a form of matter is to humans as a resource, based on its availability and *concentration*—the amount of it that is contained in a given area or volume. **High-quality matter** is highly concentrated, is typically found near the earth's surface, and has great potential for use as a resource. **Low-quality matter** is not highly concentrated, is often located deep underground or dispersed in the ocean or atmosphere, and usually has little potential for use as a resource. Figure 2-8 (p. 42) illustrates examples of differences in matter quality.

In summary, matter consists of elements and compounds that in turn are made up of atoms, ions, or molecules (**Concept 2-2**). Some forms of matter are more useful as resources than others because of their availability and concentrations.

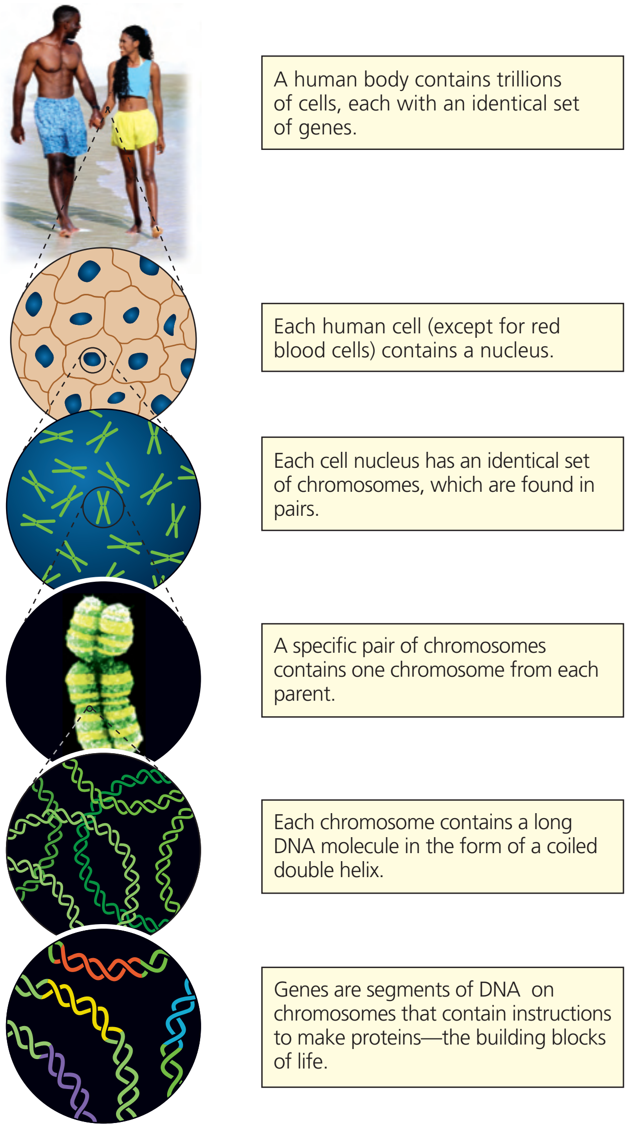


Figure 2-7 This diagram shows the relationships among cells, nuclei, chromosomes, DNA, and genes.

Figure 2-8 These examples illustrate the differences in matter quality. *High-quality matter* (left column) is fairly easy to extract and is highly concentrated; *low-quality matter* (right column) is not highly concentrated and is more difficult to extract than high-quality matter.

2-3 What Happens When Matter Undergoes Change?

▶ **CONCEPT 2-3 Whenever matter undergoes a physical or chemical change, no atoms are created or destroyed (the law of conservation of matter).**

Matter Undergoes Physical, Chemical, and Nuclear Changes

When a sample of matter undergoes a **physical change**, there is no change in its *chemical composition*. A piece of aluminum foil cut into small pieces is still aluminum foil. When solid water (ice) melts and when liquid water boils, the resulting liquid water and water vapor are still made up of H_2O molecules.

THINKING ABOUT

Controlled Experiments and Physical Changes

CORE CASE STUDY

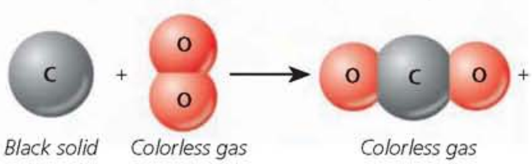
How would you set up a controlled experiment (**Core Case Study**) to verify that when water changes from one physical state to another, its chemical composition does not change?

When a **chemical change**, or **chemical reaction**, takes place, there is a change in the chemical composition of the substances involved. Chemists use a *chemical equation* to show how chemicals are rearranged in a chemical reaction. For example, coal is made up almost entirely of the element carbon (C). When coal is burned completely in a power plant, the solid carbon (C) in the coal combines with oxygen gas (O_2) from the atmosphere to form the gaseous compound carbon dioxide (CO_2). Chemists use the following shorthand chemical equation to represent this chemical reaction:

Reactant(s) ⟶ **Product(s)**

Carbon + Oxygen ⟶ Carbon dioxide + **Energy**

$C + O_2 \longrightarrow CO_2 + \text{Energy}$



In addition to physical and chemical changes, matter can undergo three types of **nuclear change**, or change in the nuclei of its atoms: radioactive decay, nuclear fission, and nuclear fusion, which are described and defined in Figure 2-9.

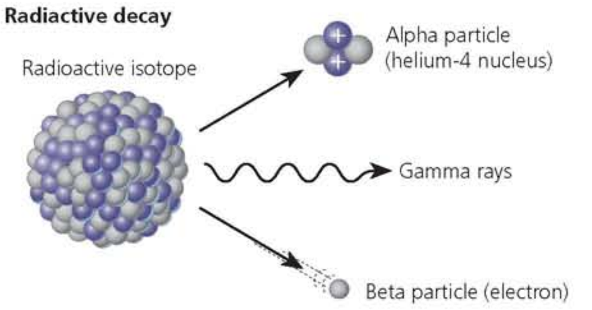
We Cannot Create or Destroy Atoms: The Law of Conservation of Matter

We can change elements and compounds from one physical or chemical form to another, but we can never create or destroy any of the atoms involved in any physical or chemical change. All we can do is rearrange the atoms, ions, or molecules into different spatial patterns (physical changes) or chemical combinations (chemical changes). These facts, based on many thousands of measurements, describe a scientific law known as the **law of conservation of matter**: Whenever matter undergoes a physical or chemical change, no atoms are created or destroyed (**Concept 2-3**).

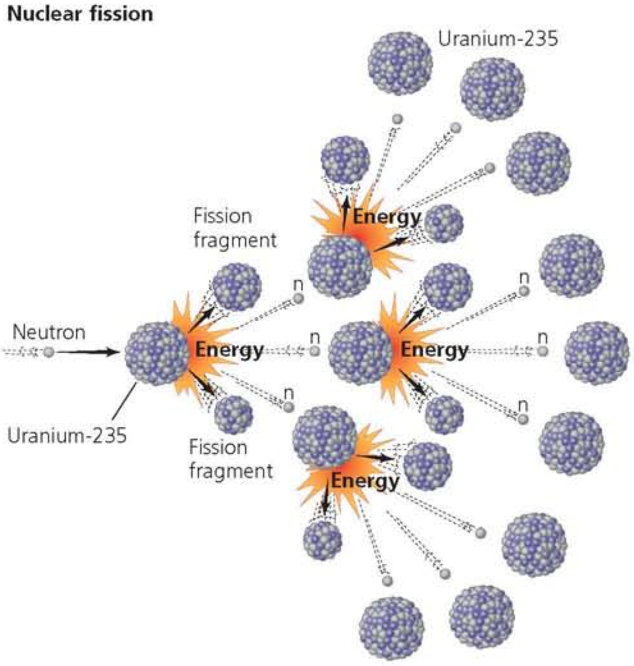
CONNECTIONS

Waste and the Law of Conservation of Matter

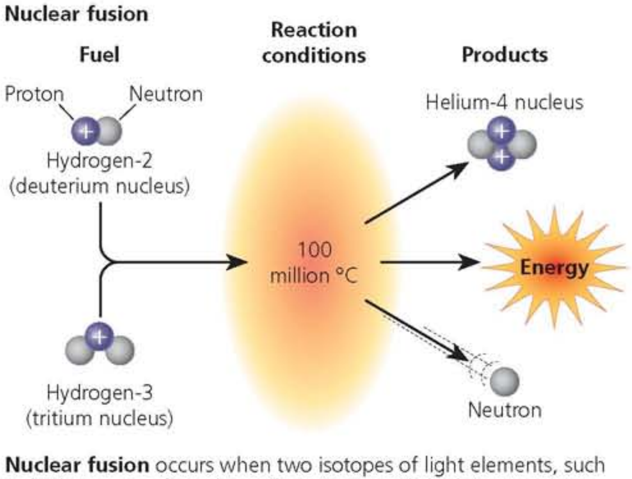
The law of conservation of matter means we can never really throw anything away because the atoms in any form of matter cannot be destroyed as it undergoes physical or chemical changes. Stuff that we put out in the trash may be buried in a sanitary landfill, but we have not really thrown it away because the atoms in this waste material will always be around in one form or another. We can burn trash, but we then end up with ash that must be put somewhere, and with gases emitted by the burning that can pollute the air. We can reuse or recycle some materials and chemicals, but the law of conservation of matter means we will always face the problem of what to do with some quantity of the wastes and pollutants we produce because their atoms cannot be destroyed.



Radioactive decay occurs when nuclei of unstable isotopes spontaneously emit fast-moving chunks of matter (alpha particles or beta particles), high-energy radiation (gamma rays), or both at a fixed rate. A particular radioactive isotope may emit any one or a combination of the three items shown in the diagram.



Nuclear fission occurs when the nuclei of certain isotopes with large mass numbers (such as uranium-235) are split apart into lighter nuclei when struck by a neutron and release energy plus two or three more neutrons. Each neutron can trigger an additional fission reaction and lead to a *chain reaction*, which releases an enormous amount of energy very quickly.



Nuclear fusion occurs when two isotopes of light elements, such as hydrogen, are forced together at extremely high temperatures until they fuse to form a heavier nucleus and release a tremendous amount of energy.

Figure 2-9 There are three types of nuclear changes: natural radioactive decay (top), nuclear fission (middle), and nuclear fusion (bottom).

2-4 What Is Energy and What Happens When It Undergoes Change?

▶ **CONCEPT 2-4A Whenever energy is converted from one form to another in a physical or chemical change, no energy is created or destroyed (first law of thermodynamics).**

▶ **CONCEPT 2-4B Whenever energy is converted from one form to another in a physical or chemical change, we end up with lower-quality or less usable energy than we started with (second law of thermodynamics).**

Energy Comes in Many Forms

Suppose you find this book on the floor and you pick it up and put it on your desktop. In doing this you have to use a certain amount of muscular force to move the book, and you have done work. In scientific terms, work is done when any object is moved a certain distance (work = force × distance). Also, whenever you touch a hot object such as a stove, heat flows from the stove to your finger. Both of these examples involve **energy**: the capacity to do work or to transfer heat.

There are two major types of energy: *moving energy* (called kinetic energy) and *stored energy* (called potential energy). Matter in motion has **kinetic energy**, which is energy associated with motion. Examples are flowing water, electricity (electrons flowing through a wire or other conducting material), and wind (a mass of moving air that we can use to produce electricity, as shown in Figure 2-10).

Another form of kinetic energy is **heat**, the total kinetic energy of all moving atoms, ions, or molecules within a given substance. When two objects at different temperatures contact one another, heat flows from the warmer object to the cooler object. You learned this the first time you touched a hot stove.

Another form of kinetic energy is called **electromagnetic radiation**, in which energy travels in the form of a *wave* as a result of changes in electrical and magnetic fields. There are many different forms of electromagnetic radiation (Figure 2-11), each having a different *wavelength* (the distance between successive peaks or troughs in the wave) and *energy content*. Forms of electromagnetic radiation with short wavelengths, such as gamma rays, X rays, and ultraviolet (UV) radiation, have more energy than do forms with longer wavelengths, such as visible light and infrared (IR) radiation. Visible light makes up most of the spectrum of electromagnetic radiation emitted by the sun.

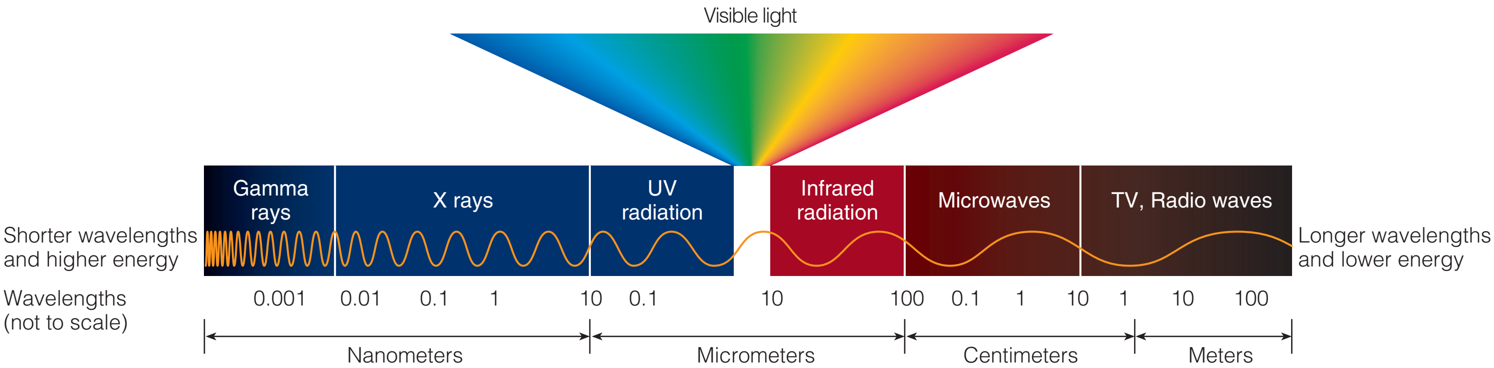
CENGAGE**NOW**™ Find out how the color, wavelengths, and energy intensities of visible light are related at CengageNOW.

The other major type of energy is **potential energy**, which is stored and potentially available for use. Examples of this type of energy include a rock held in your hand, the water in a reservoir behind a dam, and the chemical energy stored in the carbon atoms of coal.

We can change potential energy to kinetic energy. If you hold this book in your hand, it has potential energy. However, if you drop it on your foot, the book's potential energy changes to kinetic energy. When a car engine burns gasoline, the potential energy stored in the chemical bonds of the gasoline molecules changes into kinetic energy that propels the car, and into heat that flows into the environment. When water in a reservoir (Figure 2-12) flows through channels in a dam, its potential energy becomes kinetic energy that we can use to spin turbines in the dam to produce electricity—another form of kinetic energy.

Andrei Nekrassov/Shutterstock

Figure 2-10 Kinetic energy, created by the gaseous molecules in a mass of moving air, turns the blades of this wind turbine. The turbine then converts this kinetic energy to electrical energy, which is another form of kinetic energy.



CENGAGENOW™ **Active Figure 2-11** The *electromagnetic spectrum* consists of a range of electromagnetic waves, which differ in wavelength (the distance between successive peaks or troughs) and energy content. *See an animation based on this figure at* CengageNOW.

About 99% of the energy that heats the earth and our buildings, and that supports plants (through a process called photosynthesis) that provide us and other organisms with food, comes from the sun (Figure 2-13, p. 46) at no cost to us. This is in keeping with the solar energy **principle of sustainability** (see back cover). Without this essentially inexhaustible solar energy, the earth's average temperature would be −240° C (−400° F), and life as we know it would not exist.

This direct input of solar energy produces several other indirect forms of renewable solar energy. Examples are *wind* (Figure 2-10), *hydropower* (falling and flowing water, Figure 2-12), and *biomass* (solar energy converted to chemical energy and stored in the chemical bonds of organic compounds in trees and other plants).

Commercial energy sold in the marketplace makes up the remaining 1% of the energy we use to supplement the earth's direct input of solar energy. About 79% of the commercial energy used in the world and 85% of the commercial energy that is used in the United States comes from burning oil, coal, and natural gas (Figure 2-14, p. 46). These fuels are called **fossil fuels** because they were formed over millions of years as


Bryan Busovicki/Shutterstock

Figure 2-12 The water stored in this reservoir behind a dam in the U.S. state of Tennessee has potential energy, which becomes kinetic energy when the water flows through channels built into the dam where it spins a turbine and produces electricity—another form of kinetic energy.

Figure 2-13 Energy from the sun supports life and human economies. This energy is produced far away from the earth by *nuclear fusion* (Figure 2-9, bottom). In this process, nuclei of light elements such as hydrogen are forced together at extremely high temperatures until they fuse to form a heavier nucleus. This results in the release of a massive amount of energy that is radiated out through space.

Galyna Andrushko/Shutterstock

layers of the decaying remains of ancient plants and animals (fossils) were exposed to intense heat and pressure within the earth's crust.

CENGAGE**NOW**™ Witness how a Martian might use kinetic and potential energy at CengageNOW.

Some Types of Energy Are More Useful Than Others

Energy quality is a measure of the capacity of a type of energy to do useful work. **High-quality energy** has a great capacity to do useful work because it is concentrated. Examples are very high-temperature heat, concentrated sunlight, high-speed wind (Figure 2-10), and the energy released when we burn gasoline or coal.

By contrast, **low-quality energy** is so dispersed that it has little capacity to do useful work. For example, the low-temperature heat generated by the enormous number of moving molecules in the atmosphere or in an ocean (Figure 2-15) is of such low quality that we cannot use it to heat things to high temperatures.

Energy Changes Are Governed by Two Scientific Laws

Thermodynamics is the study of energy transformations. After observing and measuring energy being changed from one form to another in millions of physical and chemical changes, scientists have summarized their results in the **first law of thermodynamics**, also known as the **law of conservation of energy**. According to this scientific law, whenever energy is

Andrea Danti/Shutterstock

Tom Mc Nemar/Shutterstock

Olga Utlyakova/Shutterstock

Figure 2-14 *Fossil fuels:* Oil, coal, and natural gas (left, center, and right, respectively) supply most of the commercial energy that we use to supplement energy from the sun. Burning fossil fuels provides us with many benefits such as heat, electricity, air conditioning, manufacturing, and mobility. But when we burn these fuels, we automatically add carbon dioxide and various other pollutants to the atmosphere.

Anastasiya Igolkina/Shutterstock

Figure 2-15 A huge amount of the sun's energy is stored as heat in the world's oceans. But the temperature of this widely dispersed energy is so low that we cannot use it to heat matter to a high temperature. Thus, the ocean's stored heat is low-quality energy. **Question:** Why is direct solar energy a higher-quality form of energy than the ocean's heat is?

converted from one form to another in a physical or chemical change, no energy is created or destroyed (**Concept 2-4A**).

This scientific law tells us that no matter how hard we try or how clever we are, we cannot get more energy out of a physical or chemical change than we put in. This is one of nature's basic rules that has never been violated.

Because the first law of thermodynamics states that energy cannot be created or destroyed, but only converted from one form to another, you may be tempted to think we will never have to worry about running out of energy. Yet if you fill a car's tank with gasoline and drive around or use a flashlight battery until it is dead, something has been lost. What is it? The answer is *energy quality,* the amount of energy available for performing useful work.

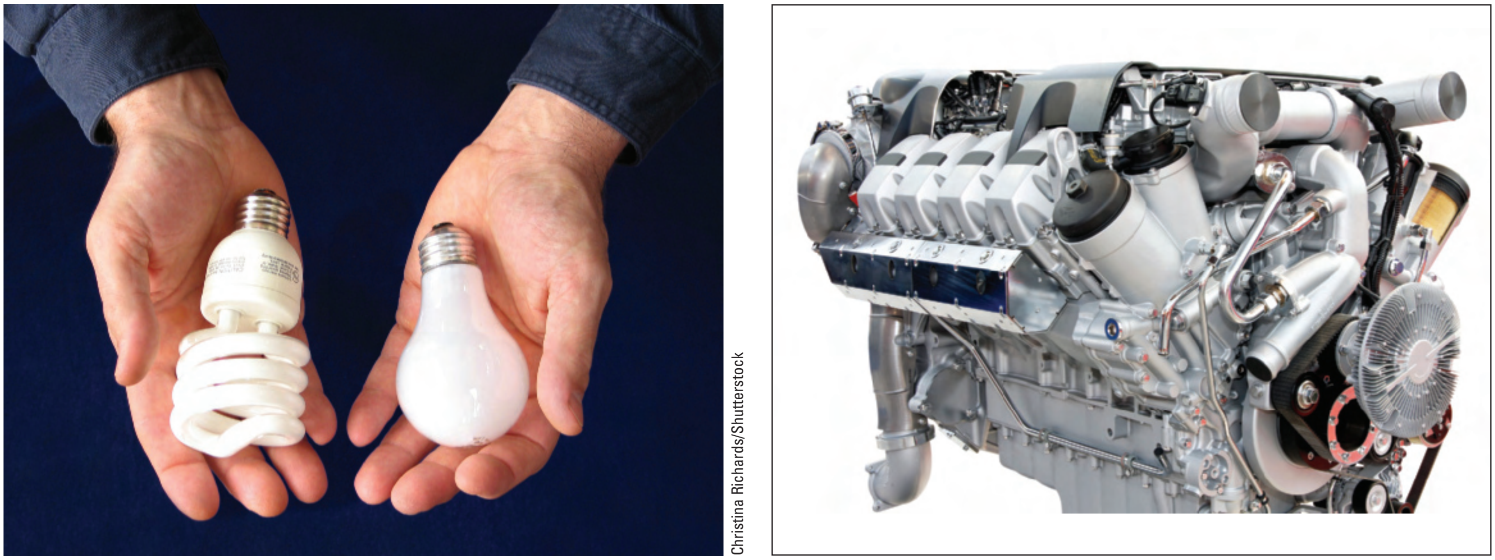
Thousands of experiments have shown that whenever energy is converted from one form to another in a physical or chemical change, we end up with lower-quality or less useable energy than we started with (**Concept 2-4B**). This is a statement of the **second law of thermodynamics**. The resulting low-quality energy usually takes the form of heat that flows into the environment. In the environment, the random motion of air or water molecules further disperses this heat, decreasing its temperature to the point where its energy quality is too low to do much useful work.

In other words, *when energy is changed from one form to another, it always goes from a more useful to a less useful form*. No one has ever found a violation of this fundamental scientific law.

We can recycle various forms of matter such as paper and aluminum. However, because of the second law of thermodynamics we can never recycle or reuse high-quality energy to perform useful work. Once the concentrated energy in a serving of food, a liter of gasoline, or a chunk of uranium is released, it is degraded to low-quality heat that is dispersed into the environment at a low temperature. According to British astrophysicist Arthur S. Eddington (1882–1944): "The second law of thermodynamics holds, I think, the supreme position among laws of nature. . . . If your theory is found to be against the second law of thermodynamics, I can give you no hope."

Two widely used technologies—the incandescent lightbulb and the internal combustion engine found in most motor vehicles—waste enormous amounts of energy (Figure 2-16, p. 48). Up to half of this waste occurs automatically because the high-quality energy in electricity and gasoline is degraded to low-quality heat that flows into the environment, as required by the second law of thermodynamics. But most of the remaining high-quality energy is wasted unnecessarily because of the poor design of these increasingly outdated technologies.

CENGAGE**NOW**™ See examples of how the first and second laws of thermodynamics apply in our world at CengageNOW.



Christina Richards/Shutterstock

Baloncici/Shutterstock

Figure 2-16 Two widely used technologies waste enormous amounts of energy. In an incandescent lightbulb (right), about 95% of the electrical energy flowing into it becomes heat; just 5% becomes light. By comparison, in a compact fluorescent bulb (left) with the same brightness, about 20% of the energy input becomes light. In the internal combustion engine (right photo) found in most motor vehicles, about 87% of the chemical energy provided in its gasoline fuel flows into the environment as low-quality heat. (Data from U.S. Department of Energy and Amory Lovins; see his Guest Essay at CengageNOW.)

2-5 What Are Systems and How Do They Respond to Change?

▶ **CONCEPT 2-5 Systems have inputs, flows, and outputs of matter and energy, and feedback can affect their behavior.**

Systems Have Inputs, Flows, and Outputs

A **system** is a set of components that function and interact in some regular way. The human body, a river, an economy, and the earth are all systems.

Most systems have the following key components: **inputs** from the environment, **flows** or **throughputs** of matter and energy within the system, and **outputs** to the environment (Figure 2-17) (**Concept 2-5**). One of the most powerful tools used by environmental scientists to study how these components of systems interact is computer modeling (Science Focus, p. 49).

Systems Respond to Change through Feedback Loops

When people ask you for feedback, they are usually seeking your response to something they said or did. They might feed your response back into their mental processes to help them decide whether and how to change what they are saying or doing.

Similarly, most systems are affected in one way or another by **feedback**, any process that increases (posi-

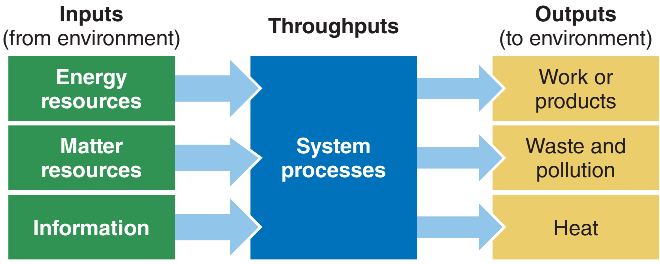


Figure 2-17 This diagram illustrates a greatly simplified model of a system. Most systems depend on inputs of matter and energy resources, and outputs of wastes, pollutants, and heat to the environment. A system can become unsustainable if the throughputs of matter and energy resources exceed the abilities of the system's environment to provide the required resource inputs and to absorb or dilute the resulting wastes, pollutants, and heat.

SCIENCE FOCUS

The Usefulness of Models

Scientists use *models*, or simulations, to learn how systems work. Mathematical models are especially useful when there are many interacting variables, when the time frame of events we are modeling is long, and when controlled experiments are impossible or too expensive to conduct. Some of our most powerful and useful technologies are mathematical models that are run on high-speed supercomputers.

Making a mathematical model usually requires that the modelers go through three steps many times. *First*, identify the major components of the system and how they interact, and develop mathematical equations that summarize this information. In succeeding runs, these equations are steadily refined. *Second*, use a high-speed computer to describe the likely behavior of the system based on the equations. *Third*, compare the system's projected behavior with known information about its actual behavior. Keep doing this until the model mimics the past and current behavior of the system.

After building and testing a mathematical model, scientists can use it to project what is *likely* to happen under a variety of conditions. In effect, they use mathematical models to answer *if–then* questions: "*If* we do such and such, *then* what is likely to happen now and in the future?" This process can give us a variety of projections of possible outcomes based on different assumptions. Mathematical models (like all other models) are no better than the assumptions on which they are built and the data we feed into them.

This process of model building was applied to the data collected by Bormann and Likens in their Hubbard Brook experiment (**Core Case Study**). Other scientists created mathematical models based on this data to describe a forest and to project what might happen to soil nutrients and other variables when the forest is disturbed or cut down.

Other areas of environmental science in which computer modeling is becoming increasingly important include studies of the complex systems that govern climate change, deforestation, biodiversity loss, and the oceans.

Critical Thinking

What are two limitations of computer models? Does this mean that we should not rely on such models? Explain.

tive feedback) or decreases (negative feedback) a change to a system (**Concept 2-5**). Such a process, called a **feedback loop**, occurs when an output of matter, energy, or information is fed back into the system as an input and leads to changes in that system. Note that, unlike the human brain, most systems do not consciously decide how to respond to feedback. Nevertheless, feedback can affect the behavior of systems.

A **positive feedback loop** causes a system to change further in the same direction (Figure 2-18). In the Hubbard Brook experiments, for example (**Core Case Study**), researchers found that when vegetation was removed from a stream valley, flowing water from precipitation caused erosion and loss of nutrients, which caused more vegetation to die. With even less vegetation to hold soil in place, flowing water caused even more erosion and nutrient loss, which caused even more plants to die.

Such accelerating positive feedback loops are of great concern in several areas of environmental science. One of the most alarming is the melting of polar ice, which has occurred as the temperature of the atmosphere has risen during the past few decades. As that ice melts, there is less of it to reflect sunlight, and more water that is exposed to sunlight. Because water is darker than ice, it absorbs more solar energy, making the polar areas warmer and causing the ice to melt faster, thus exposing more water. The melting of polar ice is therefore accelerating, causing a number of serious problems that we explore further in Chapter 19. If a system gets locked into an accelerating positive feedback loop, it can reach a breaking point that can destroy the system or change its behavior irreversibly.

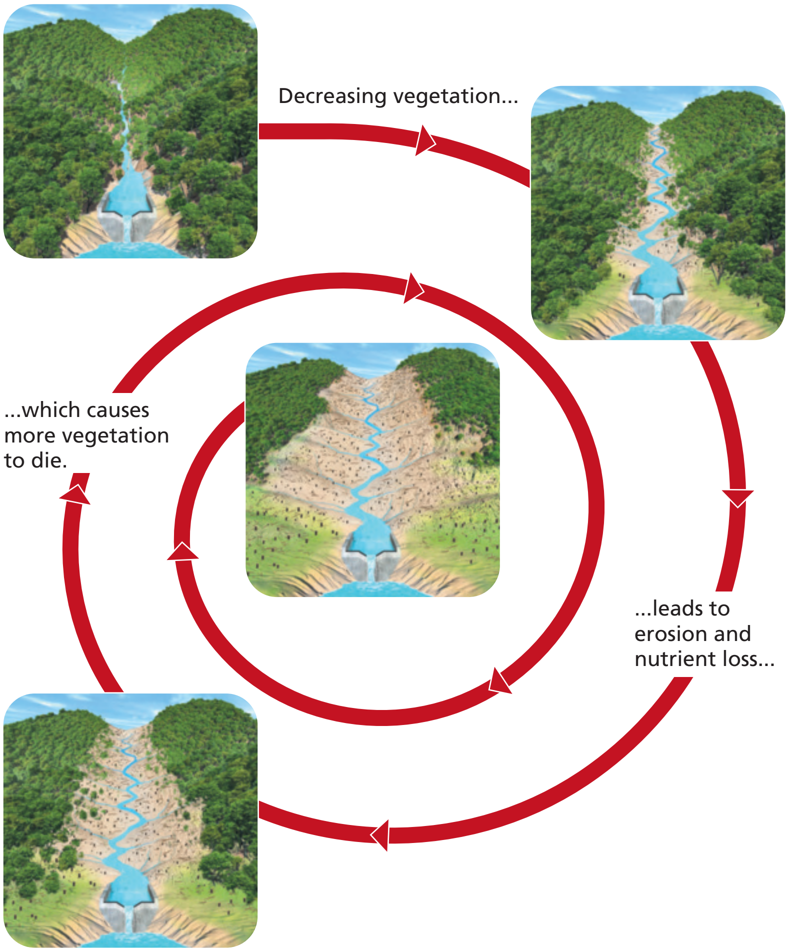


Figure 2-18 This diagram represents a *positive feedback loop*. Decreasing vegetation in a valley causes increasing erosion and nutrient losses that in turn cause more vegetation to die, resulting in more erosion and nutrient losses. **Question:** Can you think of another positive feedback loop in nature?

A **negative**, or **corrective, feedback loop** causes a system to change in the opposite direction from which is it moving. A simple example is a thermostat, a device that controls how often and how long a heating or cooling system runs (Figure 2-19). When the furnace in a house turns on and begins heating the house, we can set the thermostat to turn the furnace off when the temperature in the house reaches the set number. The house then stops getting warmer and starts to cool.

THINKING ABOUT

The Hubbard Brook Experiments and Feedback Loops

How might experimenters have employed a negative feedback loop to stop, or correct, the positive feedback loop that resulted in increasing erosion and nutrient losses in the Hubbard Brook experimental forest?

An important example of a negative feedback loop is the recycling and reuse of some resources such as aluminum and copper. For example, an aluminum can is an output of a mining and manufacturing system. When we recycle the can, that output becomes an input. This reduces the amount of aluminum ore that we must mine and process to make aluminum cans. It also reduces the harmful environmental impacts from mining and processing the aluminum ore. Such a negative feedback loop therefore can help reduce the harmful environmental impacts of human activities by decreasing the use of matter and energy resources, and the amount of pollution and solid waste produced by the use of such resources.

It Can Take a Long Time for a System to Respond to Feedback

A complex system will often show a **time delay**, or a lack of response during a period of time between the input of a feedback stimulus and the system's response to it. For example, scientists could plant trees in a degraded area such as the Hubbard Brook experimental forest to slow erosion and nutrient losses (**Core Case Study**). But it would take years for the trees and other vegetation to grow in order to accomplish this purpose.

Time delays can allow an environmental problem to build slowly until it reaches a *threshold level*, or **tipping point**—the point at which a fundamental shift in the behavior of a system occurs. Prolonged delays dampen the negative feedback mechanisms that might slow, prevent, or halt environmental problems. In the Hubbard Brook example, if soil erosion and nutrient losses reached a certain point where the land could no longer support vegetation, then a tipping point would have been reached and it would be futile to plant trees alone to try to restore the system. Other environmental prob-

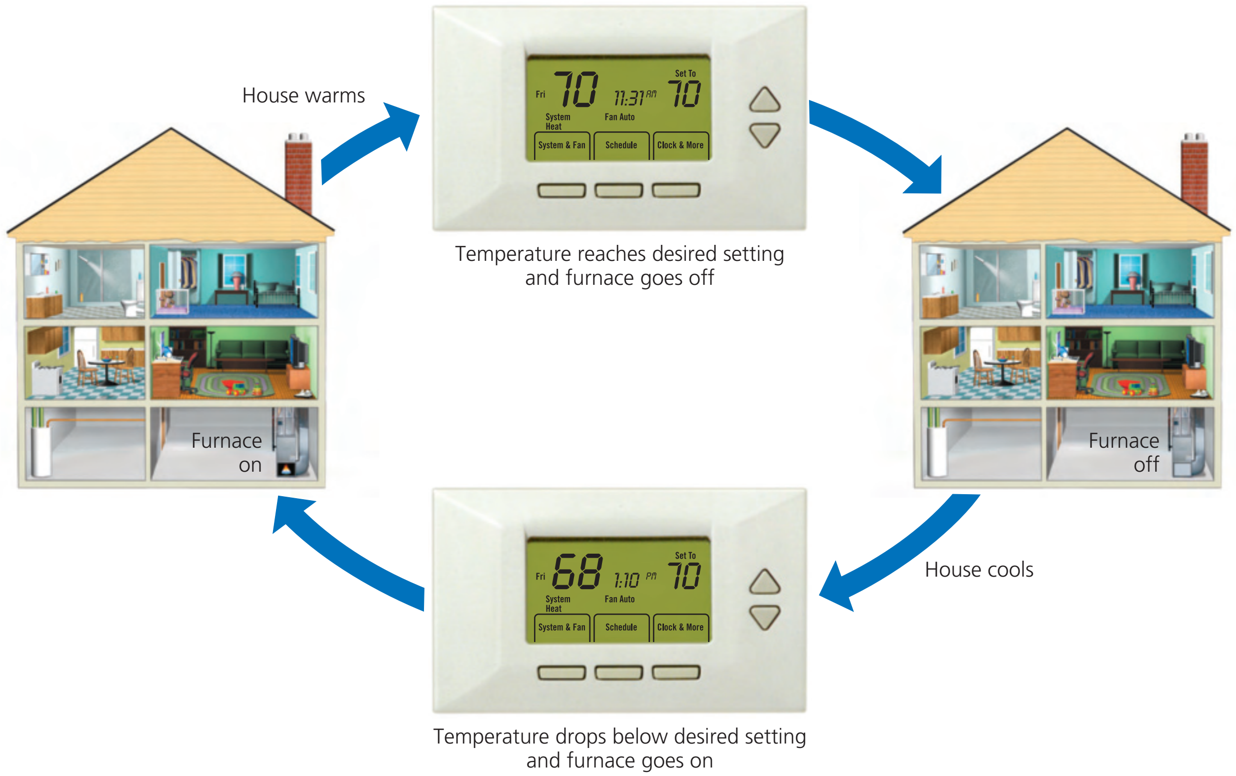


Figure 2-19 This diagram illustrates a *negative feedback loop*. When a house being heated by a furnace gets to a certain temperature, its thermostat is set to turn off the furnace, and the house begins to cool instead of continuing to get warmer. When the house temperature drops below the set point, this information is fed back to turn the furnace on until the desired temperature is reached again.

lems that can reach tipping-point levels are the melting of polar ice (as described above), population growth, and depletion of fish populations due to overfishing.

System Effects Can Be Amplified through Synergy

A **synergistic interaction**, or **synergy**, occurs when two or more processes interact so that the combined effect is greater than the sum of their separate effects. For example, scientific studies reveal such an interaction between smoking and inhaling asbestos particles. Nonsmokers who are exposed to asbestos particles for long periods of time increase their risk of getting lung cancer fivefold. But people who smoke and are exposed to asbestos have 50 times the risk that nonsmokers have of getting lung cancer.

On the other hand, synergy can be helpful. You may find that you are able to study longer or run farther if you do these activities with a studying or running partner. Your physical and mental systems can do a certain amount of work on their own. But the synergistic effect of you and your partner working together can make your individual systems capable of accomplishing more in the same amount of time.

RESEARCH FRONTIER

Identifying environmentally harmful and beneficial synergistic interactions; see **www.cengage.com/login**.

The following scientific laws of matter and energy are the *three big ideas* of this chapter:

- **There is no away.** According to the *law of conservation of matter*, no atoms are created or destroyed whenever matter undergoes a physical or chemical change. Thus, we cannot do away with matter; we can only change it from one physical state or chemical form to another.
- **You cannot get something for nothing.** According to the *first law of thermodynamics*, or the *law of conservation of energy*, whenever energy is converted from one form to another in a physical or chemical change, no energy is created or destroyed. This means that in such changes, we cannot get more energy out than we put in.
- **You cannot break even.** According to the *second law of thermodynamics*, whenever energy is converted from one form to another in a physical or chemical change, we always end up with lower-quality or less usable energy than we started with.

No matter how clever we are or how hard we try, we cannot violate these three basic scientific laws of nature that place limits on what we can do with matter and energy resources.

A Look Ahead

In the next six chapters, we apply the three basic laws of matter and thermodynamics and the three principles of sustainability (see back cover) to living systems. Chapter 3 shows how the sustainability principles related to solar energy and nutrient cycling apply in ecosystems. Chapter 4 focuses on using the biodiversity principle to understand the relationships between species diversity and evolution. Chapter 5 examines how the biodiversity principle relates to interactions among species and how such interactions regulate population size. In Chapter 6, we apply the principles of sustainability to the growth of the human population. In Chapter 7, we look more closely at terrestrial biodiversity and nutrient cycling in different types of deserts, grasslands, and forests. Chapter 8 examines biodiversity in aquatic systems such as oceans, lakes, wetlands, and rivers.

REVISITING

The Hubbard Brook Experimental Forest and Sustainability

CORE CASE STUDY

SUSTAINABILITY

The controlled experiment discussed in the **Core Case Study** that opened this chapter revealed that clearing a mature forest degrades some of its natural capital (see Figure 1-4, p. 9). Specifically, the loss of trees and vegetation altered the ability of the forest to retain and recycle water and other critical plant nutrients—a crucial ecological function based on one of the three **principles of sustainability** (see Figure 1-3, p. 8, or the back cover). In other words, the uncleared forest was a more sustainable system than a similar area of cleared forest (Figure 2-1).

This clearing of vegetation also violated the other two principles of sustainability. For example, the cleared forest lost most of its plants that had used solar energy to produce food for animals. And the loss of plants and the resulting loss of animals reduced the life-sustaining biodiversity of the cleared forest.

Humans clear forests to grow crops, build settlements, and expand cities. The key question is, how far can we go in expanding our ecological footprints (see Figure 1-13, p. 16, and **Concept 1-2**, p. 13) without threatening the quality of life for our own species and for the other species that keep us alive and support our economies? To live more sustainably, we need to find and maintain a balance between preserving undisturbed natural systems and modifying other natural systems for our use.

Logic will get you from A to B. Imagination will take you everywhere.

ALBERT EINSTEIN

REVIEW

1. Review the Key Questions and Concepts for this chapter on p. 32. Describe the *controlled scientific experiment* carried out in the Hubbard Brook Experimental Forest.

2. What is **science**? Describe the steps involved in a scientific process. What is **data**? What is a **model**? Distinguish among a **scientific hypothesis**, a **scientific theory**, and a **scientific law (law of nature)**. What is **peer review** and why is it important? Explain why scientific theories are not to be taken lightly and why people often use the term *theory* incorrectly. Describe how a hypothesis about the decline of a civilization on Easter Island has been challenged by new data.

3. Explain why scientific theories and laws are the most important and most certain results of science.

4. Distinguish among **tentative science (frontier science)**, **reliable science**, and **unreliable science**. What is **statistics**? What is **probability** and what is its role in scientific conclusions and proof? What are three limitations of science in general and environmental science in particular?

5. What is **matter**? Distinguish between an **element** and a **compound** and give an example of each. Distinguish among **atoms**, **molecules**, and **ions** and give an example of each. What is the **atomic theory**? Distinguish among **protons**, **neutrons**, and **electrons**. What is the **nucleus** of an atom? Distinguish between the **atomic number** and the **mass number** of an element. What is an **isotope**? What is **acidity**? What is **pH**?

6. What is a **chemical formula**? Distinguish between **organic compounds** and **inorganic compounds** and give an example of each. Distinguish among complex carbohydrates, proteins, nucleic acids, and lipids. What is a **cell**? Distinguish among a **gene**, a **trait**, and a **chromosome**. What is **matter quality**? Distinguish between **high-quality matter** and **low-quality matter** and give an example of each.

7. Distinguish between a **physical change** and a **chemical change (chemical reaction)** and give an example of each. What is a **nuclear change**? Explain the differences among **radioactive decay, nuclear fission**, and **nuclear fusion**. What is the **law of conservation of matter** and why is it important?

8. What is **energy**? Distinguish between **kinetic energy** and **potential energy** and give an example of each. What is **heat**? Define and give two examples of **electromagnetic radiation**. What are **fossil fuels** and what three fossil fuels do we use most to supplement energy from the sun? What is **energy quality**? Distinguish between **high-quality energy** and **low-quality energy** and give an example of each. What is the **first law of thermodynamics (law of conservation of energy)** and why is it important? What is the **second law of thermodynamics** and why is it important? Explain why the second law means that we can never recycle or reuse high-quality energy.

9. Define and give an example of a **system**. Distinguish among the **input, flow (throughput)**, and **output** of a system. Why are scientific models useful? What is **feedback**? What is a **feedback loop**? Distinguish between a **positive feedback loop** and a **negative (corrective) feedback loop** in a system, and give an example of each. Distinguish between a **time delay** and a **synergistic interaction (synergy)** in a system and give an example of each. What is a **tipping point**?

10. What are this chapter's *three big ideas*? Relate the three **principles of sustainability** to the Hubbard Brook Experimental Forest controlled experiment.

Note: Key terms are in **bold** type.

CRITICAL THINKING

1. What ecological lesson can we learn from the controlled experiment on the clearing of forests described in the **Core Case Study** that opened this chapter?

2. You observe that all of the fish in a pond have disappeared. Describe how you might use the scientific process described in the **Core Case Study** and on p. 32 to determine the cause of this fish kill.

3. Describe a way in which you have applied the scientific process described in this chapter (see Figure 2-2) in your own life, and state the conclusion you drew from this process. Describe a new problem that you would like to solve using this process.

4. Respond to the following statements:
   a. Scientists have not absolutely proven that anyone has ever died from smoking cigarettes.
   b. The natural greenhouse theory—that certain gases such as water vapor and carbon dioxide warm the lower atmosphere—is not a reliable idea because it is just a scientific theory.

5. A tree grows and increases its mass. Explain why this is not a violation of the law of conservation of matter.

6. If there is no "away" where organisms can get rid of their wastes because of the law of conservation of matter, why is the world not filled with waste matter?

7. Someone wants you to invest money in an automobile engine, claiming that it will produce more energy than the energy in the fuel used to run it. What is your response? Explain.

8. Use the second law of thermodynamics to explain why we can use oil only once as a fuel, or in other words, why we cannot recycle its high-quality energy.

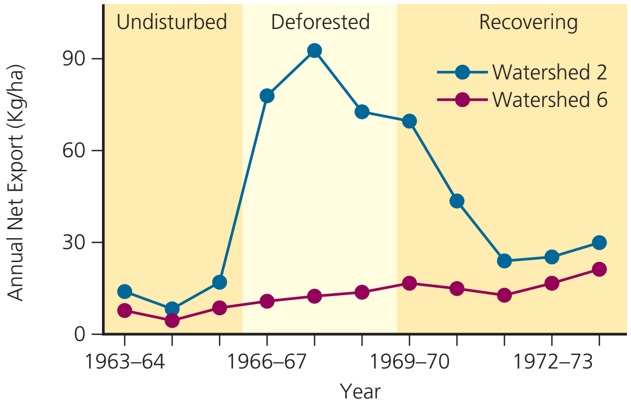
9. **a.** Imagine you have the power to revoke the law of conservation of matter for one day. What are three things you would do with this power? Explain your choices.
   b. Imagine you have the power to violate the first law of thermodynamics for one day. What are three things you would do with this power? Explain your choices.

10. List two questions that you would like to have answered as a result of reading this chapter.

DATA ANALYSIS

Consider the graph below that shows loss of calcium from the experimental cutover site of the Hubbard Brook Experimental Forest compared with that of the control site. Note that this figure is very similar to Figure 2-6, which compares loss of nitrates from the two sites (**Core Case Study**). After studying this graph, answer the questions below.

CORE CASE STUDY



1. In what year did the calcium loss from the experimental site begin a sharp increase? In what year did it peak? In what year did it again level off?

2. In what year were the calcium losses from the two sites closest together? In the span of time between 1963 and 1972, did they ever get that close again?

3. Does this graph support the hypothesis that cutting the trees from a forested area causes the area to lose nutrients more quickly than leaving the trees in place? Explain.

LEARNING ONLINE

STUDENT COMPANION SITE Visit this book's website at **www.cengagebrain.com/shop/ISBN/0538735341** and choose Chapter 2 for many study aids and ideas for further reading and research. These include flashcards, practice quizzing, Weblinks, information on Green Careers, and InfoTrac® College Edition articles.

For students with access to premium online resources, log on to **www.cengage.com/login**.

Find the latest news and research, (including videos and podcasts), at the GLOBAL ENVIRONMENT WATCH. Visit **www.CengageBrain.com** for more information.