CHAPTER

2

Environmental Systems

A Lake of Salt Water, Dust Storms, and Endangered Species

Located between the deserts of the Great Basin and the mountains of the Sierra Nevada, California's Mono Lake is an unusual site. It is characterized by eerie tufa towers of limestone rock, unique animal species, glassy waters, and frequent dust storms. Mono Lake is a *terminal lake,* which means that water flows into it, but does not flow out. As water moves through the mountains and desert soil, it picks up salt and other minerals, which it deposits in the lake. As the water evaporates, these minerals are left behind. Over time, evaporation has caused a buildup of salt concentrations so high that the lake is actually saltier than the ocean, and no fish can survive in its water.

Just when it appeared that Mono Lake would not recover, circumstances changed.

The Mono brine shrimp (*Artemia monica*) and the larvae of the Mono Lake alkali fly (*Ephydra hians*) are two of only a few animal species that can tolerate the conditions of the lake. The brine shrimp and the fly larvae consume microscopic algae, millions of tons of which grow in the lake each year. In turn, large flocks of migrating birds, such as sandpipers, gulls, and flycatchers, use the lake as a stopover, feeding on the brine shrimp and fly larvae to replenish their energy stores. The lake is an oasis on the migration route for these birds. They have come to depend on its food and water resources. The health of Mono Lake is therefore critical for many species.

In 1913, the city of Los Angeles drew up a controversial plan to redirect water away from Mono Lake and its neighbor, the larger and shallower Owens Lake. Owens Lake was diverted first, via a 359 km (223-mile) aqueduct that drew water away from the springs and streams that kept Owens Lake full. Soon, the lake began to dry up, and by the 1930s, only an empty salt flat remained. Today the dry lake bed covers roughly 440 km^2 (109,000 acres). It is one of the nation's largest sources of windblown dust, which lowers visibility in the area's national parks. Even worse, because of the local geology, the dust contains high concentrations of arsenic—a major threat to human health.

In 1941, despite the environmental degradation at Owens Lake, Los Angeles extended the aqueduct to draw water from the streams feeding Mono Lake. By 1982, with less fresh water feeding the lake, its depth had decreased by half, to an average of 14 m (45 feet), and the salinity of the water had doubled to more than twice that of the ocean. The salt killed the lake's algae. Without algae to eat, the Mono brine shrimp also died. Most birds stayed away, and newly exposed land bridges allowed coyotes from the desert to prey on those colonies of nesting birds that remained.

However, just when it appeared that Mono Lake would not recover, circumstances changed. In 1994, after years of litigation led by the National Audubon Society and tireless work by environmentalists, the Los Angeles Department of Water and Power agreed to reduce the amount of water it diverted and allow the lake to refill to about two-thirds of its historical depth. By summer 2009, lake levels had risen to just short of that goal, and the ecosystem was slowly recovering. Today brine shrimp are thriving, and many birds are returning to Mono Lake. ►

A California gull feeding on alkali flies.

◄ Tufa towers rise out of the salty water of Mono Lake.

Water is a scarce resource in the Los Angeles area, and demand there is particularly high. To decrease the amount of water diverted from Mono Lake, the city of Los Angeles had to reduce its water consumption. The city converted water-demanding grass lawns to drought-tolerant native shrubs, and it imposed new rules requiring low-flow shower heads and water-saving toilets. Through these seemingly small, but effective, measures, Los Angeles inhabitants were able to cut their water consumption and, in turn, protect nesting birds, Mono brine shrimp, and algae populations, as well as the rest of the Mono Lake ecosystem. ■

Sources: J. Kay, It's rising and healthy, *San Francisco Chronicle*, July 29, 2006; Mono Lake Committee, Mono Lake (2010), http://www.monolake.org/.

KEY IDEAS

Most problems of interest to environmental scientists involve more than one organism and more than one physical factor. Organisms, nonliving matter, and energy all interact in natural systems. Taking a systems approach to an environmental issue, rather than focusing on only one piece of the puzzle, decreases the chance of overlooking important components of that issue.

After reading this chapter you should be able to

- define *systems* within the context of environmental science.
- explain the components and states of matter.
- distinguish between various forms of energy and discuss the first and second laws of thermodynamics.
- describe the ways in which ecological systems depend on energy inputs.
- explain how scientists keep track of inputs, outputs, and changes to complex systems.
- describe how natural systems change over time and space.

Earth is a single interconnected system

The story of Mono Lake shows us that the activities of humans, the lives of other organisms, and processes in the environment are interconnected. Humans, water, animals, plants, and the desert environment all interact at Mono Lake to create a complex environmental system. The story also demonstrates a key principle of environmental science: that a change in any one factor can have other, often unexpected, effects.

In Chapter 1, we learned that a system is a set of interacting components connected in such a way that a change in one part of the system affects one or more other parts of the system. The Mono Lake system is relatively small. Other complex systems exist on a much larger scale.

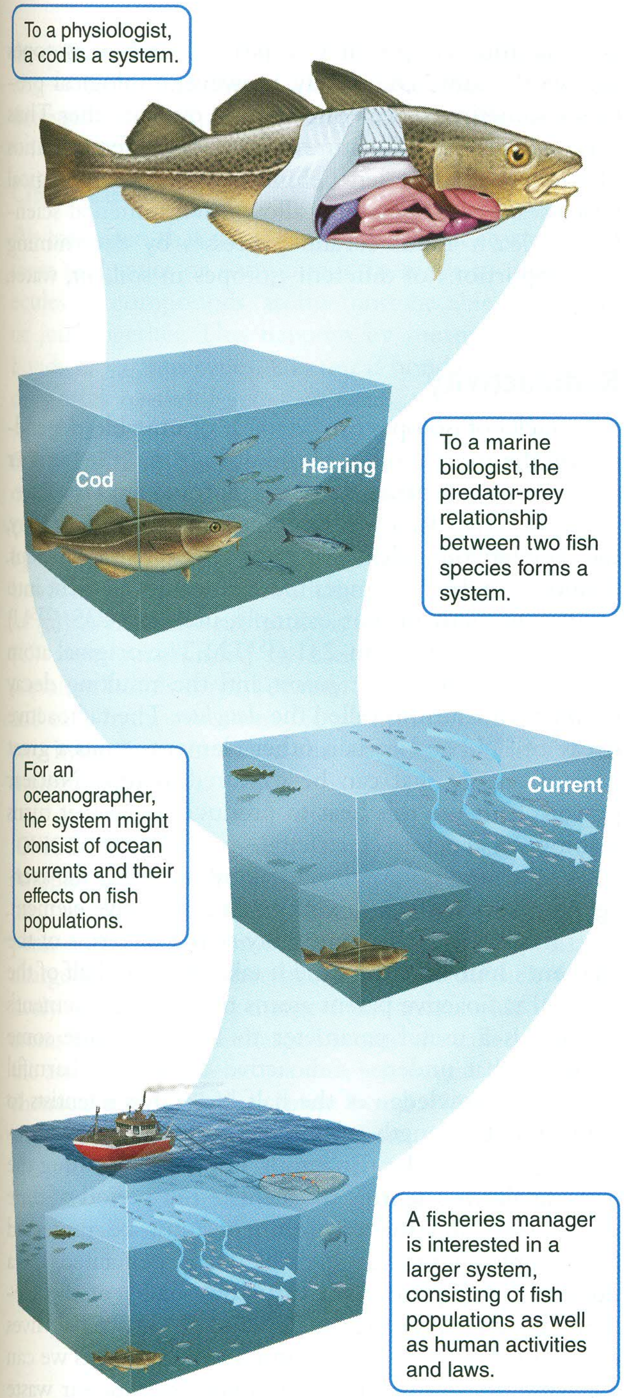
A large system may contain many smaller systems within it. **FIGURE 2.1** shows an example of complex, interconnecting systems that operate at multiple space and time scales: the fisheries of the North Atlantic. A physiologist who wants to study how codfish survive in the North Atlantic's freezing waters must consider all the biological adaptations of the cod to be part of one system. In this case, the fish and its internal organs are the system being studied. In the same environment, a marine biologist might study the predator-prey relationship between cod and herring. That relationship constitutes another system, which includes two fish species and the environment they live in. At an even larger scale, an oceanographer might focus on how ocean currents in a particular area affect the dispersal of cod and other fish species. A fisheries management official might study a system that includes all of the systems above as well as people, fishing technology, policy, and law.

The largest system that environmental science considers is Earth. Many of our most important current environmental issues—including human population growth and climate change—exist at the global scale. Throughout this book we will define a given system in terms of the environmental issue we are studying and the scale in which we are interested.

Whether we are investigating ways to reduce pollution, increase food supplies, or find alternatives to fossil fuels, environmental scientists must have a thorough understanding of matter and energy and their interactions within and across systems. We will begin this chapter by exploring the properties of matter. We will then discuss the various types of energy and how they influence and limit systems.

CHECKPOINT

- ✓ What is an environmental system? Name some examples.
- ✓ How do systems vary in scale, and how does a large system include a smaller system?
- ✓ What are the largest systems in the Mono Lake ecosystem? What are some examples of smaller systems within that system?


To a physiologist, a cod is a system.

To a marine biologist, the predator-prey relationship between two fish species forms a system.

For an oceanographer, the system might consist of ocean currents and their effects on fish populations.

A fisheries manager is interested in a larger system, consisting of fish populations as well as human activities and laws.

FIGURE 2.1 **Systems within systems.** The boundaries of an environmental system may be defined by the researcher's point of view. Physiologists, marine biologists, oceanographers, and fisheries managers would describe the North Atlantic Ocean fisheries system differently.

All environmental systems consist of matter

What do rocks, water, air, the book in your hands, and the cells in your body have in common? They are all forms of *matter.* **Matter** is anything that occupies space and has *mass.* The **mass** of an object is defined as a measure of the amount of matter it contains. Note that the words *mass* and *weight* are often used interchangeably, but they are not the same thing. Weight is the force that results from the action of gravity on mass. Your own weight, for example, is determined by the amount of gravity pulling you toward the planet's center. Whatever your weight is on Earth, you would have a lesser weight on the Moon, where the action of gravity is less. In contrast, mass stays the same no matter what gravitational influence is acting on an object. So although your weight would change on the Moon, your mass would remain the same because the amount of matter you are made of would be the same.

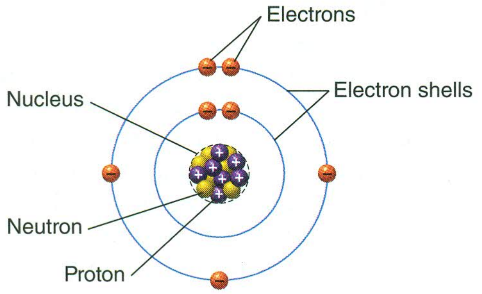
Atoms and Molecules

All matter is composed of tiny particles that cannot be broken down into smaller pieces. The basic building blocks of matter are known as atoms. An **atom** is the smallest particle that can contain the chemical properties of an element. An **element** is a substance composed of atoms that cannot be broken down into smaller, simpler components. At Earth's surface temperatures, elements can occur as solids (such as gold), liquids (such as bromine), or gases (such as helium). Atoms are so small that a single human hair measures about a few hundred thousand carbon atoms across.

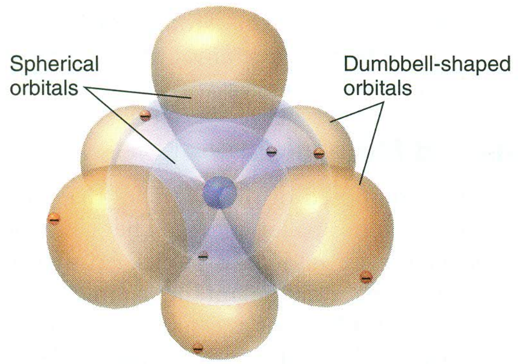
Ninety-four elements occur naturally on Earth, and another 24 have been produced in laboratories. The **periodic table** lists all of the elements currently known. (For a copy of the periodic table, turn to Appendix A.) Each element is identified by a one- or two-letter symbol; for example, the symbol for carbon is C, and the symbol for oxygen is O. These symbols are used to describe the atomic makeup of **molecules,** which are particles containing more than one atom. Molecules that contain more than one element are called **compounds.** For example, a carbon dioxide molecule (CO_2) is a compound composed of one carbon atom (C) and two oxygen atoms (O_2).

As we can see in **FIGURE 2.2a**, every atom has a *nucleus,* or core, which contains protons and neutrons. Protons and neutrons have roughly the same mass—both minutely small. Protons have a positive electrical charge, like the "plus" side of a battery. The number of protons in the nucleus of a particular element—called the **atomic number**—is unique to that element. Neutrons have no electrical charge, but they are critical to the stability of nuclei because they keep the positively charged protons together. Without them, the protons would repel one another and separate.

As **FIGURE 2.2b** shows, the space around the nucleus of the atom is not empty. In this space, electrons exist in *orbitals,* which are electron clouds that extend different distances from the nucleus. Electrons are negatively



(a) Nitrogen atom with electrons shown in shells



(b) Nitrogen atom with electrons in orbitals

FIGURE 2.2 **Structure of the atom.** An atom is composed of protons, neutrons, and electrons. Neutrons and positively charged protons make up the nucleus. Negatively charged electrons surround the nucleus. (a) Moving electrons are commonly represented in shells. (b) In reality, however, they exist in complex orbitals.

charged, like the "minus" side of a battery, and have a much smaller mass than protons or neutrons. In the molecular world, opposites always attract, so negatively charged electrons are attracted to positively charged protons. This attraction binds the electrons to the nucleus. In a neutral atom, the numbers of protons and electrons are equal. The distribution of electrons in an orbital, particularly the outermost part of the orbital, greatly contributes to the atom's chemical characteristics. In any electron orbital, there can be only a certain number of electrons.

The total number of protons and neutrons in an element is known as its **mass number.** Because the mass of an electron is insignificant compared with the mass of a proton or neutron, we do not include electrons in mass number calculations.

Although the number of protons in a chemical element is constant, atoms of the same element may have different numbers of neutrons, and therefore different mass numbers. These various kinds of atoms are called **isotopes.** Isotopes of the element carbon, for example, all have six protons, but can occur with six, seven, or eight neutrons, yielding mass numbers of 12, 13, or 14, respectively. In the natural environment, carbon occurs as a mixture of carbon isotopes. All carbon isotopes behave the same chemically. However, biological processes sometimes favor one isotope over another. Thus certain isotopic "signatures" (that is, different ratios of isotopes) can be left behind by different biological processes. These signatures allow environmental scientists to learn about certain processes by determining the proportions of different isotopes in soil, air, water, or ice.

Radioactivity

The nuclei of isotopes can be stable or unstable, depending on the mass number of the isotope and the number of neutrons it contains. Unstable isotopes are *radioactive.*

Radioactive isotopes undergo **radioactive decay,** the spontaneous release of material from the nucleus. Radioactive decay changes the radioactive element into a different element. For example, uranium-235 (^{235}U) decays to form thorium-231 (^{231}Th). The original atom (uranium) is called the *parent* and the resulting decay product (thorium) is called the *daughter.* The radioactive decay of ^{235}U and certain other elements emits a great deal of energy that can be captured as heat. Nuclear power plants use this heat to produce steam that turns turbines to generate electricity.

We measure radioactive decay by recording the average rate of decay of a quantity of a radioactive element. This measurement is commonly stated in terms of the element's **half-life:** the time it takes for one-half of the original radioactive parent atoms to decay. An element's half-life is a useful parameter to know because some elements that undergo radioactive decay emit harmful radiation. Knowledge of the half-life allows scientists to determine the length of time that a particular radioactive element may be dangerous. For example, using the half-life allows scientists to calculate the period of time that people and the environment must be protected from depleted nuclear fuel, like that generated by a nuclear power plant. As it turns out, many of the elements produced during the decay of ^{235}U have half-lives of tens of thousands of years and more. From this we can see why long-term storage of radioactive nuclear waste is so important.

The measurement of isotopes has many applications in environmental science as well as in other scientific fields. For example, carbon in the atmosphere exists in a known ratio of the isotopes carbon-12 (99 percent), carbon-13 (1 percent), and carbon-14 (which occurs in trace amounts, on the order of one part per trillion). Carbon-14 is radioactive and has a half-life of 5,730 years. Carbon-13 and carbon-12 are stable isotopes. Living organisms incorporate carbon into their tissues at roughly the known atmospheric ratio. But after an organism dies, it stops incorporating new carbon into its tissues. Over time, the radioactive carbon-14 in the organism decays to nitrogen-14. By calculating the proportion of carbon-14 in dead biological material—a technique called *carbon dating*—researchers can determine how many years ago an organism died.

Chemical Bonds

We have seen that matter is composed of atoms, which form molecules or compounds. In order to form molecules or compounds, atoms must be able to interact or join together. This happens by means of chemical bonds of various types. Chemical bonds fall into three categories: *covalent bonds, ionic bonds,* and *hydrogen bonds.*

COVALENT BONDS Elements that do not readily gain or lose electrons form compounds by sharing electrons. These compounds are said to be held together by **covalent bonds.** FIGURE 2.3 illustrates the covalent bonds in a molecule of methane (CH_4, also called *natural gas*). A methane molecule is made up of one carbon (C) atom surrounded by four hydrogen (H) atoms. Covalent bonds form between the single carbon atom and each hydrogen atom. Covalent bonds also hold the two hydrogen atoms and the oxygen atom in a water molecule together.

IONIC BONDS In a covalent bond, atoms share electrons. Another kind of bond between two atoms involves the transfer of electrons. When such a transfer happens, one atom becomes electron deficient (positively charged), and the other becomes electron rich (negatively charged). This charge imbalance holds the two atoms together. The charged atoms are called *ions,* and the attraction between oppositely charged ions forms a chemical bond called an **ionic bond.** FIGURE 2.4 shows an example of this process. Sodium (Na) donates one electron to chlorine (Cl), which gains one electron, to form sodium chloride (NaCl), or table salt.

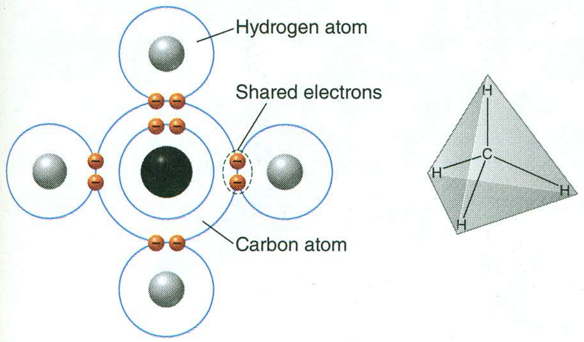


FIGURE 2.3 **Covalent bonds.** Molecules such as methane (CH_4) are associations of atoms held together by covalent bonds, in which electrons are shared between the atoms. As a result of the four hydrogen atoms sharing electrons with a carbon atom, each atom has a complete set of electrons in its outer shell—two for the hydrogen atoms and eight for the carbon atom.

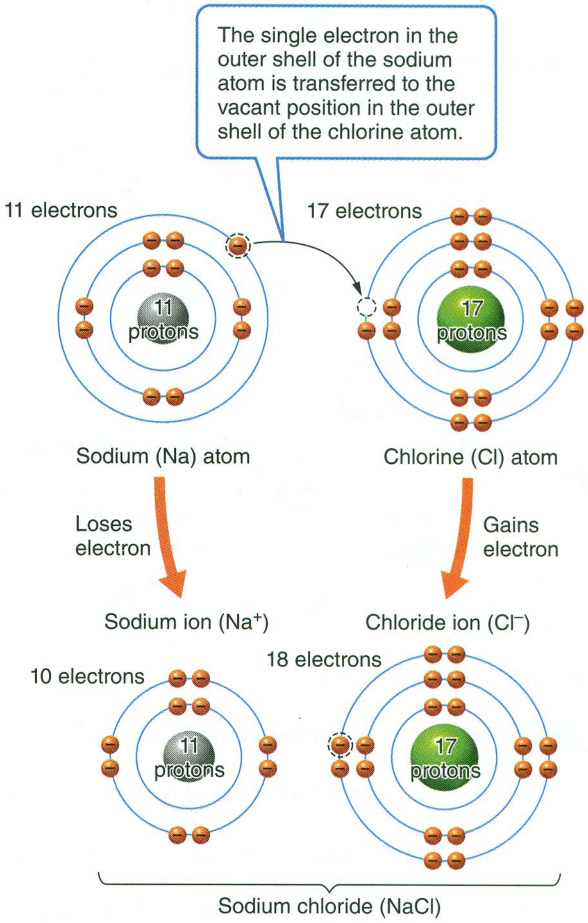
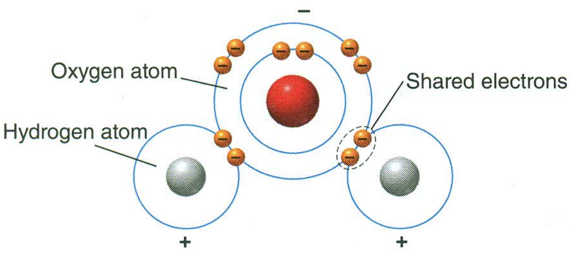


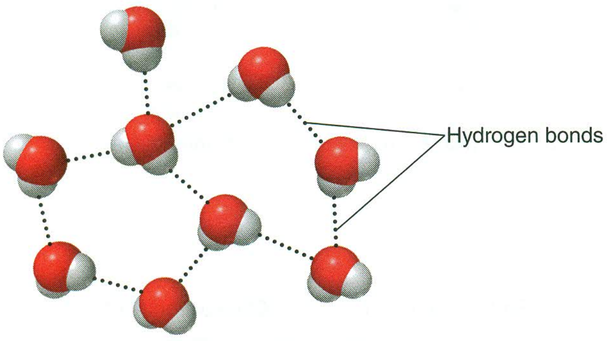
FIGURE 2.4 **Ions and ionic bonds.** A sodium atom and a chlorine atom can readily form an ionic bond. The sodium atom loses an electron, and the chlorine atom gains one. As a result, the sodium atom becomes a positively charged ion (Na$^+$) and the chlorine atom becomes a negatively charged ion (Cl$^-$, known in ionic form as chloride). The attraction between the oppositely charged ions—an ionic bond—forms sodium chloride (NaCl), or table salt.

An ionic bond is not usually as strong as a covalent bond. This means that the compound can readily dissolve. As long as sodium chloride remains in a salt shaker, it remains in solid form. But if you shake some into water, the salt dissolves into sodium and chloride ions (Na$^+$ and Cl$^-$).

HYDROGEN BONDS The third type of chemical bond is weaker than either covalent or ionic bonds. A **hydrogen bond** is a weak chemical bond that forms when hydrogen atoms that are covalently bonded to one atom are attracted to another atom on another molecule. When atoms of different elements form bonds, their electrons may be shared unequally; that is, shared electrons may be pulled closer to one atom than to the other. In some cases, the strong attraction of the hydrogen electron to other atoms creates a charge imbalance within the covalently bonded molecule.



(a) Water molecule



(b) Hydrogen bonds between water molecules

FIGURE 2.5 The polarity of the water molecule allows it to form hydrogen bonds. (a) Water (H_2O) consists of two hydrogen atoms covalently bonded to one oxygen atom. Water is a polar molecule because its shared electrons spend more time near the oxygen atom than near the hydrogen atoms. The hydrogen atoms thus have a slightly positive charge, and the oxygen atom has a slightly negative charge. (b) The slightly positive hydrogen atoms are attracted to the slightly negative oxygen atom of another water molecule. The result is a hydrogen bond between the two molecules.

Looking at FIGURE 2.5a, we see that water is an excellent example of this type of asymmetric electron distribution. Each water molecule as a whole is neutral; that is, it carries neither a positive nor a negative charge. But water has unequal covalent bonds between its two hydrogen atoms and one oxygen atom. Because of these unequal bonds and the angle formed by the H-O-H bonds, water is known as a *polar* molecule. In a **polar molecule,** one side is more positive and the other side is more negative. We can see the result in FIGURE 2.5b: a hydrogen atom in a water molecule is attracted to the oxygen atom in a nearby water molecule. That attraction forms a hydrogen bond between the two molecules.

By allowing water molecules to link together, hydrogen bonding gives water a number of unusual properties. Hydrogen bonds also occur in nucleic acids such as DNA, the biological molecule that carries the genetic code for all organisms.

Properties of Water

The molecular structure of water gives it unique properties that support the conditions necessary for life on Earth. Among these properties are surface tension, capillary action, a high boiling point, and the ability to dissolve many different substances—all essential to physiological functioning.

SURFACE TENSION AND CAPILLARY ACTION We don't generally think of water as being sticky, but hydrogen bonding makes water molecules stick strongly to one another (*cohesion*) and to certain other substances (*adhesion*). The ability to cohere or adhere underlies two unusual properties of water: *surface tension and capillary action*.

Surface tension, which results from the cohesion of water molecules at the surface of a body of water, creates a sort of skin on the water's surface. Have you ever seen an aquatic insect, such as a water strider, walk across the surface of the water? This is possible because of surface tension (FIGURE 2.6). Surface tension also makes water droplets smooth and more or less spherical as they cling to a water faucet before dropping.

Capillary action happens when adhesion of water molecules to a surface is stronger than cohesion between the molecules. The absorption of water by a paper towel or a sponge is the result of capillary action. This property is important in thin tubes, such as the water-conducting vessels in tree trunks, and in small pores in soil. It is also important in the transport of underground water, as well as dissolved pollutants, from one location to another.

BOILING AND FREEZING At the atmospheric pressures found at Earth's surface, water boils (becomes a gas) at

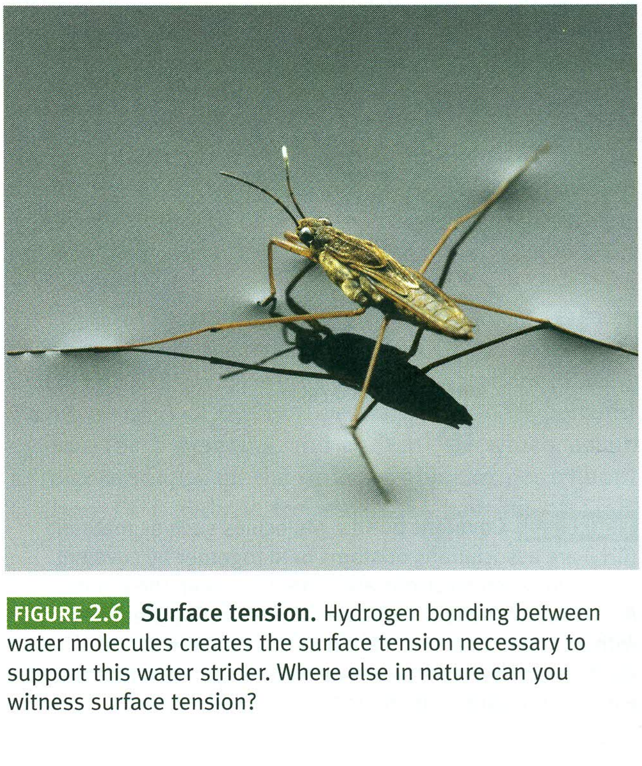


FIGURE 2.6 Surface tension. Hydrogen bonding between water molecules creates the surface tension necessary to support this water strider. Where else in nature can you witness surface tension?

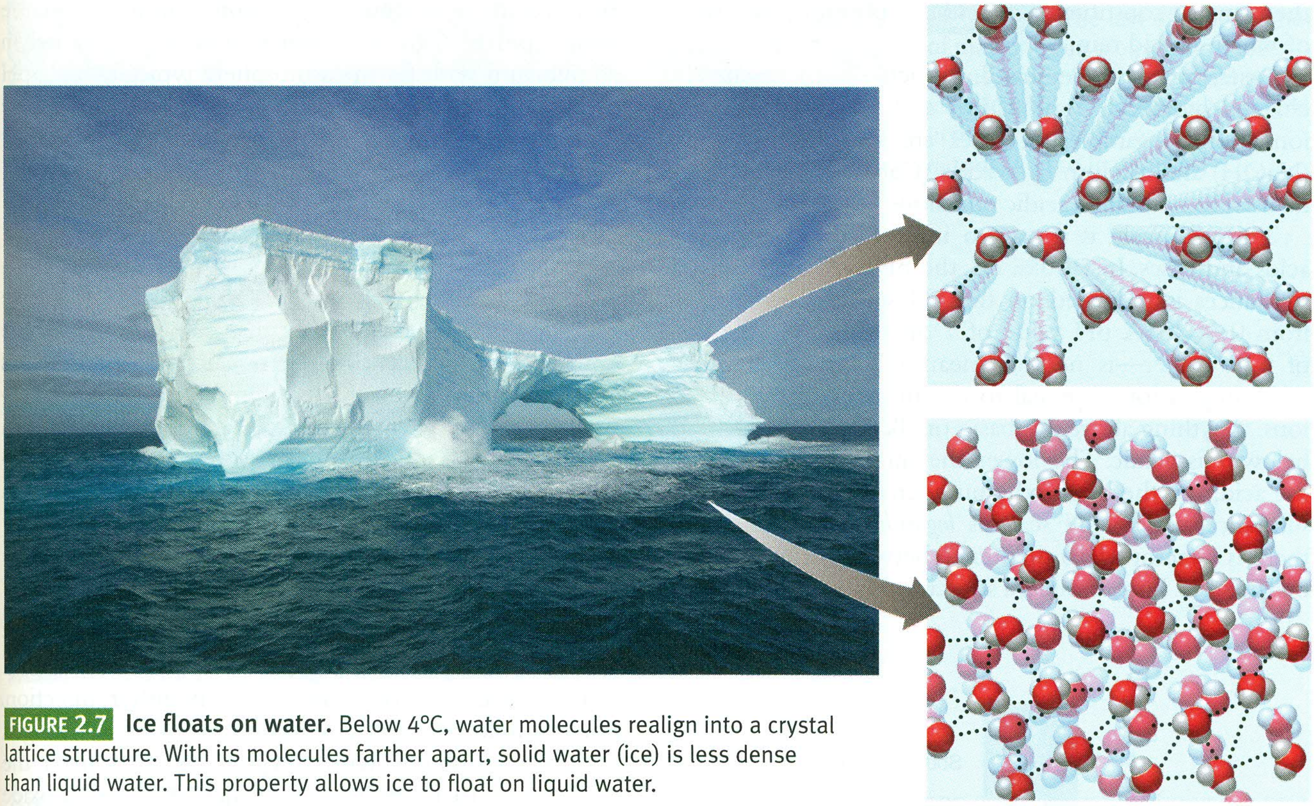


FIGURE 2.7 **Ice floats on water.** Below 4°C, water molecules realign into a crystal lattice structure. With its molecules farther apart, solid water (ice) is less dense than liquid water. This property allows ice to float on liquid water.

100°C (212°F) and freezes (becomes a solid) at 0°C (32°F). If water behaved like structurally similar compounds such as hydrogen sulfide (H_2S), which boils at –60°C (–76°F), it would be a gas at typical Earth temperatures, and life as we know it could not exist. Because of its cohesion, however, water can be a solid, a gas, or—most importantly for living organisms—a liquid at Earth's surface temperatures. In addition, the hydrogen bonding between water molecules means that it takes a great deal of energy to change the temperature of water. Thus the water in organisms protects them from wide temperature swings. Hydrogen bonding also explains why geographic areas near large lakes or oceans have moderate climates. The water body holds summer heat, slowly releasing it as the atmosphere cools in the fall, and warms only slowly in spring, thereby preventing the adjacent land area from heating up quickly.

Water has another unique property: it takes up a larger volume in solid form than it does in liquid form. FIGURE 2.7 illustrates the difference in structure between liquid water and ice. As liquid water cools, it becomes denser, until it reaches 4°C (39°F), the temperature at which it reaches maximum density. As it cools from 4°C down to freezing at 0°C, however, its molecules realign into a crystal lattice structure, and its volume expands. You can see the result any time you add an ice cube to a drink: ice floats on liquid water.

What does this unique property of water mean for life on Earth? Imagine what would happen if water acted like most other liquids. As it cooled, it would continue to become denser. Its solid form (ice) would sink, and lakes and ponds would freeze from the bottom up. As a result, very few aquatic organisms could survive in temperate and cold climates.

WATER AS A SOLVENT In our table salt example, we saw that water makes a good solvent. Many substances, such as table salt, dissolve well in water because their polar molecules bond easily with other polar molecules. This explains the high concentrations of dissolved ions in seawater as well as the capacity of living organisms to store many types of molecules in solution in their cells. Unfortunately, many toxic substances also dissolve well in water, which makes them easy to transport through the environment.

Acids, Bases, and pH

Another important property of water is its ability to dissolve hydrogen- or hydroxide-containing compounds known as *acids* and *bases*. An **acid** is a substance that contributes hydrogen ions to a solution. A **base** is a substance that contributes hydroxide ions to a solution. Both acids and bases typically dissolve in water.

When an acid is dissolved in water, it dissociates into positively charged hydrogen ions (H^+) and negatively charged ions. Two important acids we will discuss in this book are nitric acid (HNO_3) and sulfuric acid (H_2SO_4),

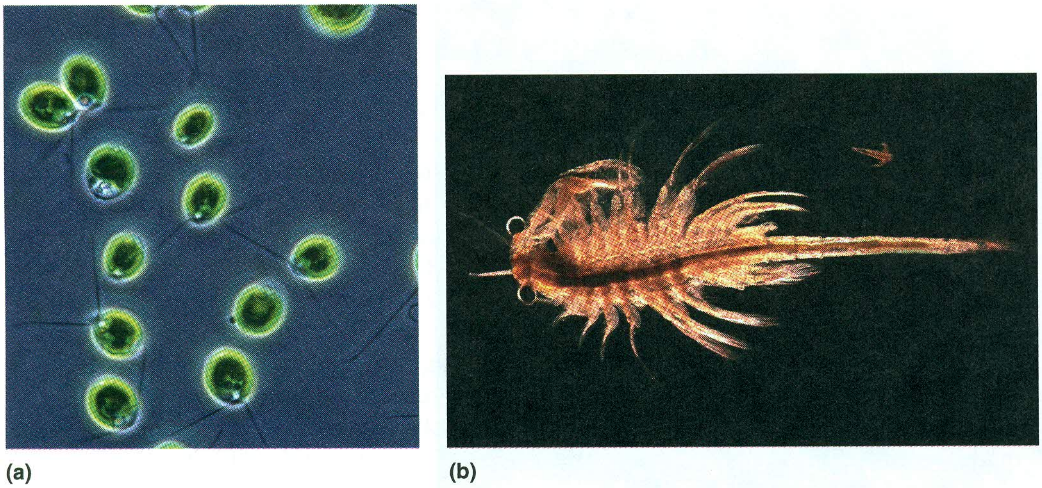


FIGURE 2.10 **Organisms are composed of cells.** (a) Some organisms, such as these green algae, consist of a single cell. (b) More complex organisms, such as the Mono brine shrimp, are made up of millions of cells.

A **cell** is a highly organized living entity that consists of the four types of macromolecules and other substances in a watery solution, surrounded by a *membrane.* Some organisms, such as most bacteria and some algae, consist of a single cell. That one cell contains all of the functional structures, or *organelles,* needed to keep the cell alive and allow it to reproduce (FIGURE 2.10a). Larger and more complex organisms, such as Mono Lake's brine shrimp, are multicellular (FIGURE 2.10b).

CHECKPOINT

- ✓ What are the three types of chemical bonds?
- ✓ What are the unique properties of water? In what ways do those properties make life possible on Earth?
- ✓ What are the four types of biological molecules, and how do they differ from one another?

Energy is a fundamental component of environmental systems

Earth's systems cannot function, and organisms cannot survive, without *energy.* **Energy** is the ability to do work, or transfer heat. Water flowing into a lake has energy because it moves and can move other objects in its path. All living systems absorb energy from their surroundings and use it to organize and reorganize molecules within their cells and to power movement. Plants absorb solar energy and use it in photosynthesis to convert carbon dioxide and water into sugars, which they then use to survive, grow, and reproduce. The sugars in plants are also an important energy source for many animals. Humans, like other animals, absorb the energy they need for cellular respiration from food. This provides the energy for our daily activities, from waking to sleeping and everything in between.

Ultimately, most energy on Earth derives from the Sun. The Sun emits **electromagnetic radiation,** a form of energy that includes, but is not limited to, visible light, ultraviolet light, and infrared energy, which we perceive as heat. The scale at the top of FIGURE 2.11 shows these and other types of electromagnetic radiation.

Electromagnetic radiation is carried by **photons,** massless packets of energy that travel at the speed of light and can move even through the vacuum of space. The amount of energy contained in a photon depends on its *wavelength*—the distance between two peaks or troughs in a wave, as shown in the inset in Figure 2.11. Photons with long wavelengths, such as radio waves, have very low energy, while those with short wavelengths, such as X-rays, have high energy. Photons of different wavelengths are used by humans for different purposes.

Forms of Energy

The basic unit of energy in the metric system is the *joule* (abbreviated J). A **joule** is the amount of energy used when a 1-watt light bulb is turned on for 1 second—a very small amount. Although the joule is the preferred energy unit in scientific study, many other energy units are commonly used. Conversions between these units and joules are given in Table 2.1.

ENERGY AND POWER Energy and *power* are not the same thing, even though we often use the words inter-

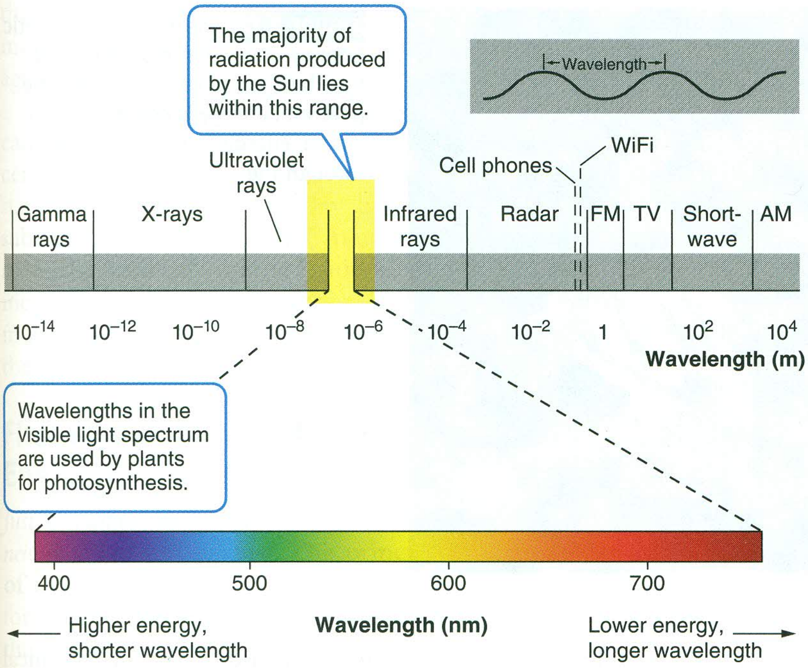


FIGURE 2.11 The electromagnetic spectrum. Electromagnetic radiation can take numerous forms, depending on its wavelength. The Sun releases photons of various wavelengths, but primarily between 250 and 2,500 nanometers (nm) (1 nm = 1×10^{-9} m).

changeably. Energy is the ability to do work, whereas **power** is the rate at which work is done:

$$\text{energy} = \text{power} \times \text{time}$$
$$\text{power} = \text{energy} \div \text{time}$$

When we talk about generating electricity, we often hear about kilowatts and kilowatt-hours. The kilowatt (kW) is a unit of power. The kilowatt-hour (kWh) is a unit of energy. Therefore, the capacity of a turbine is given in kW because that measurement refers to the turbine's power. Your monthly home electricity bill reports energy use—the amount of energy from electricity that you have used in your home—in kWh. Do the Math "Calculating Energy Use and Converting Units" gives you an opportunity to practice working with these units.

KINETIC AND POTENTIAL ENERGY Energy takes a variety of forms. Many stationary objects possess a large amount of **potential energy**—energy that is stored but has not yet been released. Water impounded behind a dam contains a great deal of potential energy. When the water is released and flows downstream, that potential energy becomes **kinetic energy,** the energy of motion (FIGURE 2.12). The kinetic energy of moving water can be captured at a dam and transferred to a turbine and generator, and ultimately to the energy in electricity. Can you think of other common examples of kinetic energy? A car moving down the street, a flying honeybee, and a football travelling through the air all have kinetic energy. Sound also has kinetic energy because it travels in waves through the coordinated motion of atoms. Systems can contain potential energy, kinetic energy, or some of each.

TABLE 2.1 Common units of energy and their conversion into joules

Unit	Definition	Relationship to joules	Common uses
calorie	Amount of energy it takes to heat 1 gram of water 1°C	1 calorie = 4.184 J	Energy expenditure and transfer in ecosystems; human food consumption
Calorie	Food calorie; always shown with a capital C	1 Calorie = 1,000 calories = 1 kilocalorie (kcal)	Food labels; human food consumption
British thermal unit (Btu)	Amount of energy it takes to heat 1 pound of water 1°F	1 Btu = 1,055 J	Energy transfer in air conditioners and home and water heaters
kilowatt-hour (kWh)	Amount of energy expended by using 1 kilowatt of electricity for 1 hour	1 kWh = 3,600,000 J = 3.6 megajoules (MJ)	Energy use by electrical appliances, often given in kWh per year

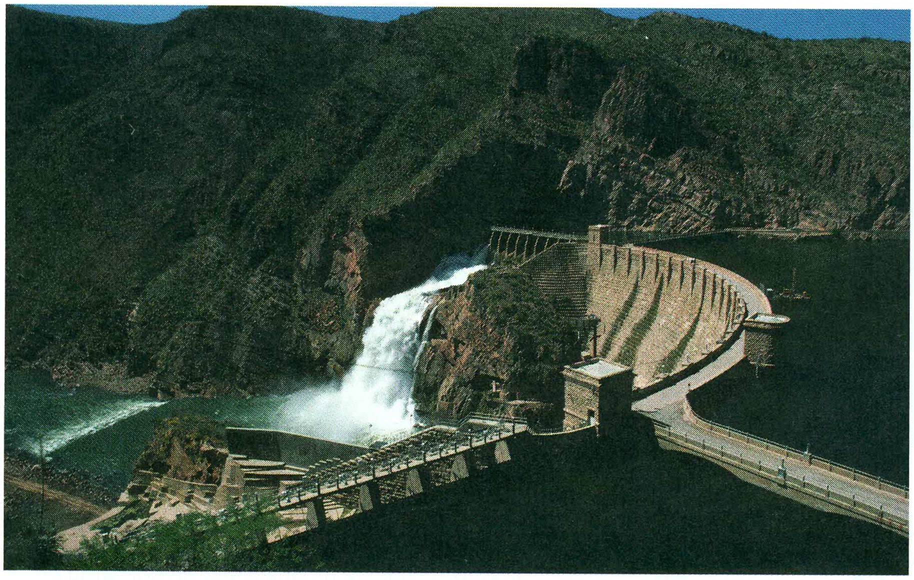


FIGURE 2.12 **Potential and kinetic energy.** The water stored behind this dam has potential energy. The potential energy is converted into kinetic energy as the water flows through the gates.

Potential energy stored in chemical bonds is known as **chemical energy.** The energy in food is a familiar example. By breaking down the high-energy bonds in the pizza you had for lunch, your body obtains energy to power its activities and functions. Likewise, an automobile engine combusts gasoline and releases its chemical energy to propel the car.

TEMPERATURE All matter, even the frozen water in the world's ice caps, contains some energy. When we say

DO THE MATH

Calculating Energy Use and Converting Units

Your electricity bill shows that you use 600 kWh of electricity each month. Your refrigerator, which is 15 years old, could be responsible for up to 25 percent of this electricity consumption. Newer refrigerators are more efficient, meaning that they use less energy to do the same amount of work. If you wish to conserve electrical energy and save money, should you replace your refrigerator? How can you compare the energy efficiency of your old refrigerator with that of the more efficient new models?

Your refrigerator uses 500 watts when the motor is running. The motor runs for about 30 minutes per hour (or a total of 12 hours per day).

1. How much energy does your refrigerator use?

$$0.5 \text{ kW} \times 12 \text{ hours/day} = 6 \text{ kWh/day}$$

$$6 \text{ kWh/day} \times 365 \text{ days/year} = 2{,}190 \text{ kWh/year}$$

2. How much more efficient is the best new refrigerator compared with your older model?

The best new model uses 400 kWh per year. Your refrigerator uses 2,190 kWh per year.

$$2{,}190 \text{ kWh/year} - 400 \text{ kWh/year} = 1{,}790 \text{ kWh/year}$$

3. Assume that you are paying, on average, $0.10 per kilowatt-hour for electricity. A new refrigerator would cost you $550. You will receive a rebate of $50 from your electric company for purchasing an energy-efficient refrigerator. If you replace your refrigerator, how long will it be before your energy savings compensate you for the cost of the new appliance?

You will save

$$1{,}790 \text{ kWh/year} \times \$0.10\text{/kWh} = \$179\text{/year}$$

Dividing $500 by $179 indicates that in less than 3 years, you will recover the cost of the new appliance.

Your Turn: Environmental scientists must often convert energy units in order to compare various types of energy. For instance, you might want to compare the energy you would save by purchasing an energy-efficient refrigerator with the energy you would save by driving a more fuel-efficient car. Assume that for the amount you would spend on the new refrigerator ($500), you can make repairs to your car engine that would save you 20 gallons (76 liters) of gasoline per month (1 liter of gasoline contains the energy equivalent of about 10 kWh). Using this information and Table 2.1, convert the quantities of both gasoline and electricity into joules and compare the energy savings. Which decision would save the most energy?

that energy moves matter, we mean that it is moving the molecules within a substance. The measure of the average kinetic energy of a substance is its **temperature.**

Changes in temperature—and, therefore, in energy—can convert matter from one state to another. At a certain temperature, the molecules in a solid substance start moving so fast that they begin to flow, and the substance melts into a liquid. At an even higher temperature, the molecules in the liquid move even faster, with increasing amounts of energy. Finally the molecules move with such speed and energy that they overcome the forces holding them together and become gases.

First Law of Thermodynamics: Energy Is Conserved

Just as matter can neither be created nor destroyed, energy is neither created nor destroyed. This principle is the **first law of thermodynamics.** Like matter, energy also changes form. So, when water is released from behind a dam, the potential energy of the impounded water becomes the kinetic energy of the water rushing through the gates of the dam.

The first law of thermodynamics dictates that you can't get something from nothing. When an organism needs biologically usable energy, it must convert it from an energy source such as the Sun or food. The potential energy contained in firewood never goes away, but is transformed into heat energy permeating a room when the wood is burned in a fireplace. Sometimes it may be difficult to identify where the energy is going, but it is always conserved.

Look at FIGURE 2.13, which uses a car to show the first law in action through a series of energy conversions. Think of the car, including its fuel tank, as a system. The potential energy of the fuel (gasoline) is converted into kinetic energy when the battery supplies a spark in the presence of gasoline and air. The gasoline combusts, and the resulting gases expand, pushing the pistons in the engine—converting the chemical energy in the gasoline into the kinetic energy of the moving pistons. Energy is transferred from the pistons to the drive train, and from there to the wheels, which propel the car. The combustion of gasoline also produces heat, which dissipates into the environment outside the system. The kinetic energy of the moving car is converted into heat and sound energy as the tires create friction with the road and the body of the automobile moves through the air. When the brakes are applied to stop the car, friction between brake parts releases heat energy. No energy is ever destroyed in this example, but chemical energy is converted into motion, heat, and sound. Notice that some of the energy stays within the system and some (such as the heat from burning gasoline) leaves the system.

Second Law of Thermodynamics

We have seen how the potential energy of gasoline is transformed into the kinetic energy of moving pistons in a car engine. But as Figure 2.13 shows, some of that energy is converted into a less usable form—in this case, heat. The heat that is created is called waste heat, meaning that it is not used to do any useful work. The **second law of thermodynamics** tells us that *when energy is transformed, the quantity of energy remains the same, but its ability to do work diminishes.*

ENERGY EFFICIENCY To quantify this observation, we use the concept of *energy efficiency.* **Energy efficiency** is the ratio of the amount of work that is done to the total amount of energy that is introduced into the system in the first place. Two machines or engines that perform the same amount of work, but use different amounts of energy to do that work, have different energy efficiencies. Consider the difference between modern woodstoves and traditional open fireplaces. A woodstove that is 70 percent efficient might use 2 kg of wood to heat a room to a comfortable 20°C (68°F), whereas a fireplace that is 10 percent efficient would require 14 kg

FIGURE 2.13 **Conservation of energy within a system.** In a car, the potential energy of gasoline is converted into other forms of energy. Some of that energy leaves the system, but all of it is conserved.

(a) Traditional fireplace

(b) Modern woodstove

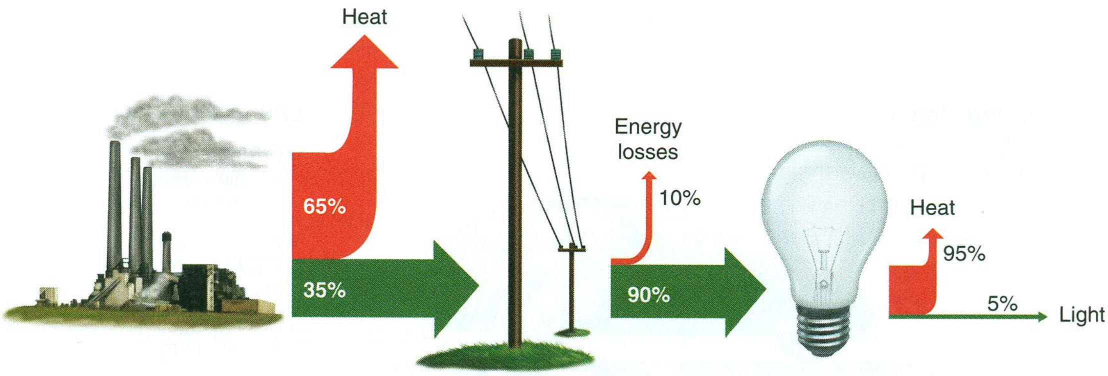
FIGURE 2.14 **Energy efficiency.** (a) The energy efficiency of a traditional fireplace is low because so much heated air can escape through the chimney. (b) A modern woodstove, which can heat a room using much less wood, is much more energy efficient.

to achieve the same temperature—a sevenfold greater energy input (**FIGURE 2.14**).

We can also calculate the energy efficiency of transforming one form of energy into other forms of energy. Let's consider what happens when we convert the chemical energy of coal into the electricity that operates a reading lamp and the heat that the lamp releases. **FIGURE 2.15** shows the process.

A modern coal-burning power plant can convert 1 metric ton of coal, containing 24,000 megajoules (MJ; 1 MJ = 1 million joules) of chemical energy into about 8,400 MJ of electricity. Since 8,400 is 35 percent of 24,000, this means that the process of turning coal into electricity is about 35 percent efficient. The rest of the energy from the coal—65 percent—is lost as waste heat. In the electrical transmission lines between the power plant and the house, 10 percent of the electrical energy from the plant is lost as heat and sound, so the transport of energy away from the plant is about 90 percent efficient. We know that the conversion of electrical energy into light in an incandescent bulb is 5 percent efficient; again, the rest of the energy is lost as heat. From beginning to end, we can calculate the energy efficiency of converting coal into incandescent lighting by multiplying all the individual efficiencies:

0.35	×	0.90	×	0.05	=	0.016 (1.6% efficiency)
coal to electricity	×	transport of electricity	×	light bulb efficiency	=	overall efficiency



Calculation: (35%) × (90%) × (5%) = 1.6% efficiency

FIGURE 2.15 **The second law of thermodynamics.** Whenever one form of energy is transformed into another, some of that energy is converted into a less usable form of energy, such as heat. In this example, we see that the conversion of coal into the light of an incandescent bulb is only 1.6 percent efficient.

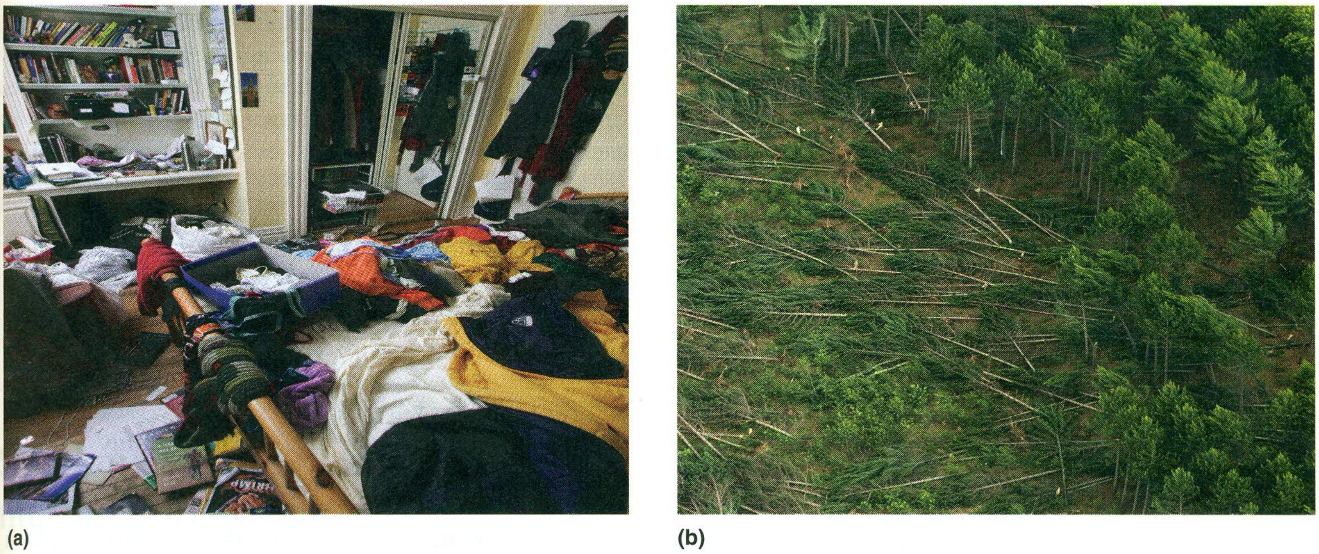


FIGURE 2.16 **Energy and entropy.** Entropy increases in a system unless an input of energy from outside the system creates order. (a) In order to reduce the entropy of this messy room, a human must expend energy, which comes from food. (b) A tornado has increased the entropy of this forest system in Wisconsin.

ENERGY QUALITY Related to energy efficiency is **energy quality,** the ease with which an energy source can be used for work. A high-quality energy source has a convenient, concentrated form so that it does not take too much energy to move it from one place to another. Gasoline, for example, is a high-quality energy source because its chemical energy is concentrated (about 44 MJ/kg), and because we have technology that can conveniently transport it from one location to another. In addition, it is relatively easy to convert gasoline energy into work and heat. Wood, on the other hand, is a lower-quality energy source. It has less than half the energy concentration of gasoline (about 20 MJ/kg) and is more difficult to use to do work. Imagine using wood to power an automobile. Clearly, gasoline is a higher-quality energy source than wood. Energy quality is one important factor humans must consider when they make energy choices.

ENTROPY The second law of thermodynamics also tells us that all systems move toward randomness rather than toward order. This randomness, called **entropy,** is always increasing in a system, unless new energy from outside the system is added to create order.

Think of your bedroom as a system. At the start of the week, your books may be in the bookcase, your clothes may be in the dresser, and your shoes may be lined up in a row in the closet. But what happens if, as the week goes on, you don't expend energy to put your things away (FIGURE 2.16)? Unfortunately, your books will not spontaneously line up in the bookcase, your clothes will not fall folded into the dresser, and your shoes will not pair up and arrange themselves in the closet. Unless you bring energy into the system to put things in order, your room will slowly become more and more disorganized.

The energy you use to pick up your room comes from the energy stored in food. Food is a relatively high-quality energy source because the human body easily converts it into usable energy. The molecules of food are ordered rather than random. In other words, food is a low-entropy energy source. Only a small portion of the energy in your digested food is converted into work, however; the rest becomes body heat, which may or may not be needed. This waste heat has a high degree of entropy because heat is the random movement of molecules. Thus, in using food energy to power your body to organize your room, you are decreasing the entropy of the room, but increasing the entropy in the universe by producing waste body heat.

Another example of the second law can be found in the observation that energy always flows from hot to cold. A pot of water will never boil without an input of energy, but hot water left alone will gradually cool as its energy dissipates into the surrounding air. This application of the second law is important in many of the global circulation patterns that are powered by the energy of the Sun.

CHECKPOINT

- ✓ What is the difference between power and energy? Why is it important to know the difference?
- ✓ How do potential energy and kinetic energy differ? What is chemical energy?
- ✓ What are the first and second laws of thermodynamics?

Energy conversions underlie all ecological processes

Life requires order. If organisms were not made up of molecules organized into structures such as proteins and cells, they could not grow—in fact, they could never develop in the first place. All living things work against entropy by using energy to maintain order.

Individual organisms rely on a continuous input of energy in order to survive, grow, and reproduce. But interactions at levels beyond the organism can also be seen as a process of converting energy into organization. Consider a forest ecosystem. Trees absorb water through their roots and carbon dioxide through their leaves. By combining these compounds in the presence of sunlight, they convert water and carbon dioxide into sugars that will provide them with the energy they need. Trees fight entropy by keeping their atoms and molecules together in tree form, rather than having them dispersed randomly throughout the universe. But then a deer grazes on tree leaves, and later a mountain lion eats the deer. At each step, energy is converted by organisms into work.

The form and amount of energy available in an environment determines what kinds of organisms can live there. Plants thrive in tropical rainforests where there is plenty of sunlight as well as water. Many food crops, not surprisingly, can be planted and grown in temperate climates that have a moderate amount of sunlight. Life is much more sparse at high latitudes, toward the North and South Poles, where less solar energy is available to organisms. The landscape is populated mainly by small plants and shrubs, insects, and migrating animals. Plants cannot live at all on the deep ocean floor, where no solar energy penetrates. The animals that live there, such as eels, anglerfish, and squid, get their energy by feeding on dead organisms that sink from above. Chemical

FIGURE 2.17 **The amount of available energy determines which organisms can live in a natural system.** (a) A tropical rainforest has abundant energy available from the Sun and enough moisture for plants to make use of that energy. (b) The Arctic tundra has much less energy available, so plants grow more slowly there and do not reach large sizes. (c) Organisms, such as this squid, living at the bottom of the ocean must rely on dead biological matter falling from above. (d) The energy supporting this deep-ocean vent community comes from chemicals emitted from the vent. Bacteria convert the chemicals into forms of energy that other organisms, such as tube worms, can use.

energy, in the form of sulfides emitted from deep-ocean vents (underwater geysers), supports a plantless ecosystem that includes sea spiders, 2.4 meter (8-foot) tube worms, and bacteria (FIGURE 2.17).

CHECKPOINT

- ✓ Provide an example of how organisms convert energy from one form into another.
- ✓ How does energy determine the suitability of an environment for growing food?

Systems analysis shows how matter and energy flow in the environment

Why is it important for environmental scientists to study whole systems rather than focusing on the individual plants, animals, or substances within a system? Imagine taking apart your cell phone and trying to understand how it works simply by focusing on the microphone. You wouldn't get very far. Similarly, it is important for environmental scientists to look at the whole picture, not just the individual parts of a system, in order to understand how that system works.

Studying systems allows scientists to think about how matter and energy flow in the environment. In this way, researchers can learn about the complex relationships between organisms and the environment, but more importantly, they can predict how changes to any part of the system—for example, changes in the water level at Mono Lake—will change the entire system.

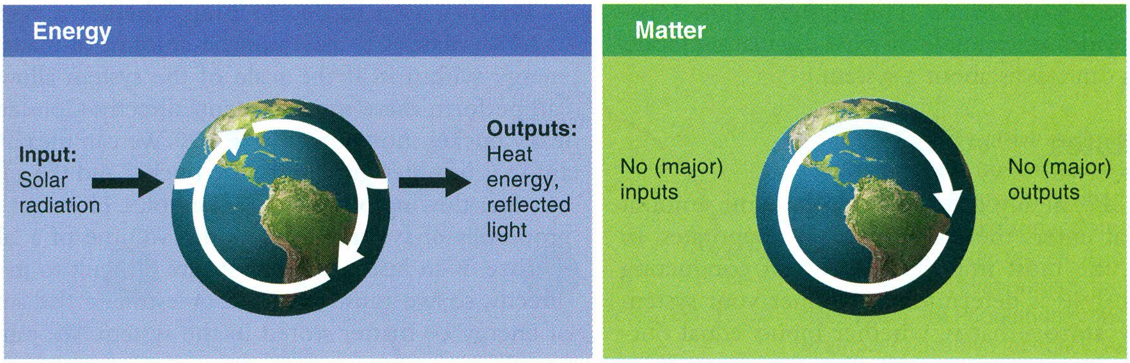
Systems can be either *open* or *closed*. In an **open system,** exchanges of matter or energy occur across system boundaries. Most systems are open. Even at remote Mono Lake, water flows in, and birds fly to and from the lake. The ocean is also an open system. Energy from the Sun enters the ocean, warming the waters and providing energy to plants and algae. Energy and matter are transferred from the ocean to the atmosphere as energy from the Sun evaporates water, giving rise to meteorological events such as tropical storms, in which clouds form and send rain back to the ocean surface. Matter, such as sediment and nutrients, enters the ocean from rivers and streams and leaves it through geologic cycles and other processes.

In a **closed system,** matter and energy exchanges across system boundaries do not occur. Closed systems are less common than open systems. Some underground cave systems are nearly completely closed systems.

As FIGURE 2.18 shows, Earth is an open system with respect to energy. Solar radiation enters Earth's atmosphere, and heat and reflected light leave it. But because of its gravitational field, Earth is essentially a closed system with respect to matter. Only an insignificant amount of material enters or leaves the Earth system. All important material exchanges occur within the system.

Inputs and Outputs

By now you have seen numerous examples of both **inputs,** or additions to a given system, and **outputs,** or losses from the system. People who study systems often conduct a **systems analysis,** in which they determine inputs, outputs, and changes in the system under various conditions. For instance, researchers studying Mono Lake might quantify the inputs to that system—such as water and salts—and the outputs—such as water that evaporates from the lake and brine shrimp removed by migratory birds. Because no water flows out of the lake, salts are not removed, and even without the aqueduct, Mono Lake, like other terminal lakes, would slowly



(a) Open system

(b) Closed system

FIGURE 2.18 **Open and closed systems.** (a) Earth is an open system with respect to energy. Solar radiation enters the Earth system, and energy leaves it in the form of heat and reflected light. (b) However, Earth is essentially a closed system with respect to matter because very little matter enters or leaves the Earth system. The white arrows indicate the cycling of energy and matter.

DO THE MATH

The Mystery of the Missing Salt

Before the Los Angeles Aqueduct was built, about 120 billion liters of stream water (31 billion gallons) flowed into Mono Lake in an average year. As a terminal lake, it had no outflow streams. The water level did not rise or fall in an average year. Therefore, the water in the lake had to be going somewhere to balance the water coming in; if the system size was not changing, then inputs must equal outputs. In this case, roughly the same amount of water that entered the lake must have evaporated. The salt content of the stream water flowing into Mono Lake varied, but a typical liter of stream water averaged 50 mg of salt.

1. How much salt entered Mono Lake annually?

To calculate the total amount of salt that entered Mono Lake each year, we can multiply the amount of salt (50 mg) per liter of water by the number of liters of water flowing into the lake (120 billion per year):

$$50\ \text{mg/L} \times 120\ \text{billion L/year} =$$
$$6\ \text{trillion mg/year} = 6\ \text{million kg/year}$$

2. The lake today contains about 285 billion kilograms of dissolved salt. At the rate of salt input we have just calculated, how long would it take to accumulate that much salt, starting with zero salt in the lake?

We have just determined that the salt concentration of Mono Lake increases by 6 million kilograms per year. Mono Lake contains approximately 285 billion kilograms of dissolved salts today, so at the rate of stream flow before the diversion, it would have taken about 47,500 years to accumulate that much salt:

$$285\ \text{billion kg} \div 6\ \text{million kg/year} = 47{,}500\ \text{years}$$

3. No water has flowed out of the Mono Lake basin since it was formed about 120,000 years ago. Assume that Earth's climate hasn't changed much over that time. At today's input rate, how much salt should be in the water of Mono Lake today?

$$6\ \text{million kg/year} \times 120{,}000\ \text{years} = 720\ \text{billion kg}$$

4. The salt loads in questions 2 and 3 do not agree. How can we explain the discrepancy?

The lake's towering tufa formations hold the answer: many of the salts (including calcium and sodium) have precipitated—that is, separated—out of the water to form the tufa rock. In this way, the salts have been removed from the water, but not from the Mono Lake system as a whole. Our analysis is complete when we account for the salts removed from the lake as tufa. FIGURE 2.19 summarizes these inputs to and outputs from the Mono Lake system.

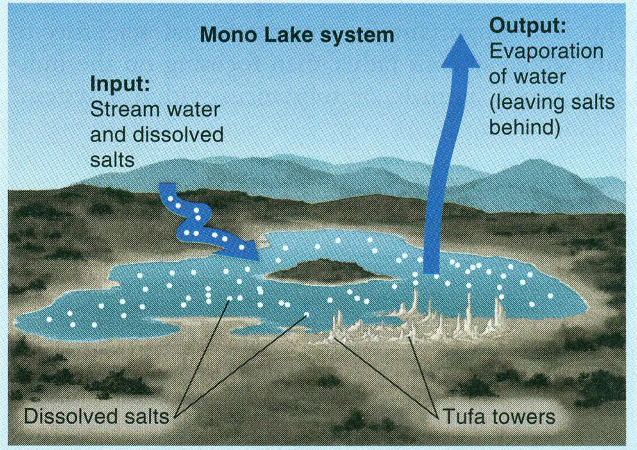


FIGURE 2.19 **Inputs to and outputs from the Mono Lake ecosystem.**

become saltier. Do the Math "The Mystery of the Missing Salt" provides an example of what calculating inputs and outputs can tell us about a system.

Steady States

At Mono Lake, in any given period, the same amount of water that enters the lake eventually evaporates. In many cases, the most important aspect of conducting a systems analysis is determining whether your system is in **steady state**—that is, whether inputs equal outputs, so that the system is not changing over time. This information is particularly useful in the study of environmental science. For example, it allows us to know whether the amount of a valuable resource or harmful pollutant is increasing, decreasing, or staying the same.

The first step in determining whether a system is in steady state is to measure the amount of matter and energy within it. If the scale of the system allows, we can perform these measurements directly. Consider the leaky bucket shown in FIGURE 2.20. We can measure the amount of water going into the bucket and the amount of water flowing out through the holes. However, some properties of systems, such as the volume of a lake or the size of an insect population, are difficult to measure directly, so we must calculate or estimate the amount of energy or matter stored in the system. We can then use this information to determine the inputs to and outputs from the system to determine whether it is in steady state.

Many aspects of natural systems, such as the water vapor in the global atmosphere, have been in steady state

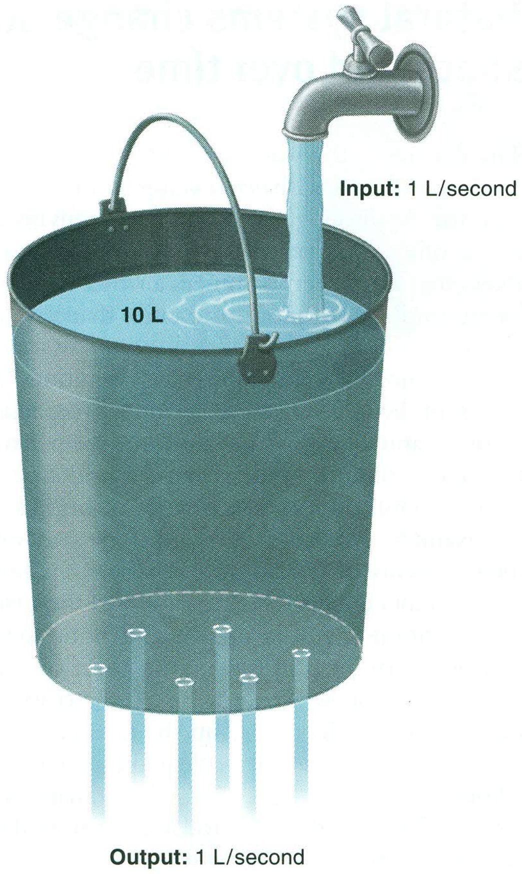


FIGURE 2.20 **A system in steady state.** In this leaky bucket, inputs equal outputs. As a result, there is no change in the total amount of water in the bucket: the system is in steady state.

for at least as long as we have been studying them. The amount of water that enters the atmosphere by evaporation from oceans, rivers, and lakes is roughly equal to the amount that falls from the atmosphere as precipitation. Until recently, the oceans have also been in steady state: the amount of water that enters from rivers and streams has been roughly equal to the amount that evaporates into the air. One concern about the effects of global climate change is that some global systems, such as the system that includes water balance in the oceans and atmosphere, may no longer be in steady state.

It's interesting to note that one part of a system can be in steady state while another part is not. Before the Los Angeles Aqueduct was built, the Mono Lake system was in steady state with respect to water (the inflow of water equaled the rate of water evaporation), but *not* with respect to salt: salt was slowly accumulating, as it does in all terminal lakes.

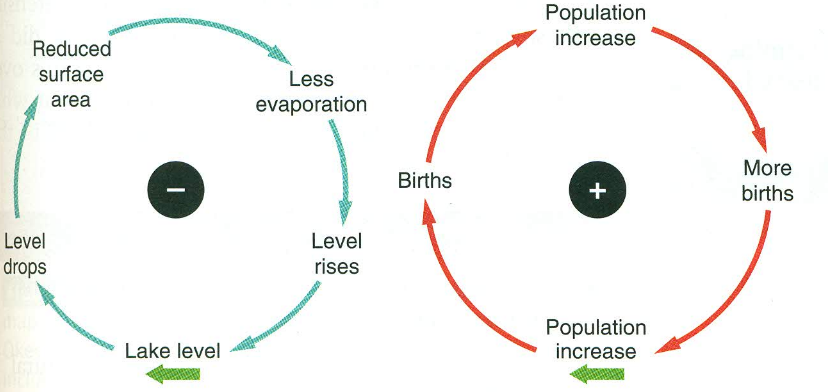
Feedbacks

Most natural systems are in steady state. Why? A natural system can respond to changes in its inputs and outputs. For example, during a period of drought, evaporation from a lake will be greater than precipitation and stream water flowing into the lake. Therefore, the lake will begin to dry up. Soon there will be less surface water available for evaporation, and the evaporation rate will continue to fall until it matches the new, lower precipitation rate. When this happens, the system returns to steady state, and the lake stops shrinking.

Of course, the opposite is also true. In very wet periods, the size of the lake will grow, and evaporation from the expanded surface area will continue to increase until the system returns to a steady state at which inputs and outputs are equal.

Adjustments in input or output rates caused by changes to a system are called *feedbacks.* The term **feedback** means that the results of a process *feed back* into the system to change the rate of that process. Feedbacks, which can be diagrammed as loops or cycles, are found throughout the environment.

There are two kinds of feedback, *negative* and *positive.* In natural systems, scientists most often observe **negative feedback loops,** in which a system responds to a change by returning to its original state, or at least by decreasing the rate at which the change is occurring. FIGURE 2.21a shows a negative feedback loop for Mono Lake: when



(a) Negative feedback loop

(b) Positive feedback loop

FIGURE 2.21 **Negative and positive feedback loops.** (a) A negative feedback loop occurs at Mono Lake: when the water level drops, the lake surface area is reduced, and evaporation decreases. As a result of the decrease in evaporation, the lake level rises again. (b) Population growth is an example of positive feedback. As members of a species reproduce, they create more offspring that will be able to reproduce in turn, creating a cycle that increases the population size. The green arrow indicates the starting point of each cycle.

water levels drop, there is less lake surface area, so evaporation decreases as well. With less evaporation, the water in the lake slowly returns to its original volume.

Positive feedbacks also occur in the natural world. FIGURE 2.21b shows an example of how births in a population can give rise to a **positive feedback loop.** The more members of a species that can reproduce, the more births there will be, creating even more of the species to give birth, and so on.

It's important to note that *positive* and *negative* here do not mean *good* and *bad;* instead, positive feedback *amplifies* changes, whereas negative feedback *resists* changes. People often talk about the balance of nature. That balance is the logical result of systems reaching a state at which negative feedbacks predominate—although positive feedback loops play important roles in environmental systems as well.

One of the most important questions in environmental science is to what extent Earth's temperature is regulated by feedback loops, and if so, what types, and at what scale. In general, warmer temperatures at Earth's surface increase the evaporation of water. The additional water vapor that enters the atmosphere by evaporation causes two kinds of clouds to form. Low-altitude clouds reflect sunlight back into space. The result is less heating of Earth's surface, less evaporation, and less warming—a negative feedback loop. High-altitude clouds, on the other hand, absorb terrestrial energy that might have otherwise escaped the atmosphere, leading to higher temperatures near Earth's surface, more evaporation of water, and more warming—a positive feedback loop. In the absence of other factors that compensate for or balance the warming, this positive feedback loop will continue making temperatures warmer, driving the system further away from its starting point. This and other potential positive feedback loops may play critical roles in climate change.

The health of many environmental systems depends on the proper operation of feedback loops. Sometimes, natural or anthropogenic factors lead to a breakdown in a negative feedback loop and drive an environmental system away from its steady state. This is particularly true when a new component is added to a system, as with the introduction of an invasive species, or when humans use too much of a natural resource. As you study the exploitation of natural resources, try to determine what factors may be disrupting the negative feedback loops of the systems that provide those resources.

CHECKPOINT

- ✓ What is an open system? What is a closed system?
- ✓ Why is it important to look at a whole system rather than only at its parts?
- ✓ What is steady state? What are feedback loops? Why are they important?

Natural systems change across space and over time

The decline in the water level of Mono Lake was caused by people: humans diverted water from the lake for their own use. Anthropogenic change in an environmental system is often very visible. We see anthropogenic change in rivers that have been dammed, air that has been polluted by automobile emissions, and cities that have encroached on once wild areas.

Differences in environmental conditions affect what grows or lives in an area, creating geographic variation among natural systems. Variations in temperature, precipitation, or soil composition across a landscape can lead to vastly different numbers and types of organisms. In Texas, for example, sycamore trees grow in river valleys where there is plenty of water available, whereas pine trees dominate mountain slopes because they can tolerate the cold, dry conditions there. Paying close attention to these natural variations may help us predict the effect of any change in an environment. So we know that if the rivers that support the sycamores in Texas dry up, the trees will probably die.

Natural systems are also affected by the passage of time. Thousands of years ago, when the climate of the Sahara was much wetter than it is today, it supported large populations of Nubian farmers and herders. Small changes in Earth's orbit relative to the Sun, along with a series of other factors, led to the disappearance of monsoon rains in northern Africa. As a result, the Sahara—now a desert nearly the size of the continental United States—became one of Earth's driest regions. Other, more dramatic changes have occurred on the planet. In the last few million years, Earth has moved in and out of several ice ages; 70 million years ago, central North America was covered by a sea; 240 million years ago, Antarctica was warm enough for 6-foot-long salamander-like amphibians to roam its swamps. Natural systems respond to such changes in the global environment with migrations and extinctions of species as well as the evolution of new species.

Throughout Earth's history, small natural changes have had large effects on complex systems, but human activities have increased both the pace and the intensity of these natural environmental changes, as they did at Mono Lake. Studying variations in natural systems over space and time can help scientists learn more about what to expect from the alterations humans are making to the world today.

CHECKPOINT

- ✓ Give some examples of environmental conditions that might vary among natural systems.
- ✓ Why is it important to study variation in natural systems over space and time?

WORKING TOWARD SUSTAINABILITY

Managing Environmental Systems in the Florida Everglades

South Florida's vast Everglades ecosystem extends over 50,000 km^2 (12,500,000 acres) (**FIGURE 2.22**). The region, which includes the Everglades and Biscayne Bay national parks, is home to many threatened and endangered bird, mammal, reptile, and plant species, including the Florida panther (*Puma concolor coryi*) and the Florida manatee (*Trichechus manatus latirostris*). The 4,000 km^2 (988,000-acre) subtropical wetland area for which the region is best known has been called a "river of grass" because a thin sheet of water flows constantly through it, allowing tall water-tolerant grasses to grow (**FIGURE 2.23**).

A hundred years of rapid human population growth, and the resulting need for water and farmland, have had a dramatic impact on the region. Flood control, dams, irrigation, and the need to provide fresh water to Floridians have led to a 30 percent decline in water flow through the Everglades. Much of the water that does flow through the region is polluted by phosphorus-rich fertilizer and waste from farms and other sources upstream. Cattails thrive on the input of phosphorus, choking out other native plants. The reduction in water flow and water quality is, by most accounts, destroying the Everglades. Can we save this natural system while still providing water to the people who need it?

The response of scientists and policy makers has been to treat the Everglades as a set of interacting systems and manage the inputs and outputs of water and pollutants to those systems. The Comprehensive Everglades Restoration Plan of 2000 is a systems-based approach to the region's problems. It covers 16 counties and 46,600 km^2 (11,500,000 acres) of South Florida. The plan is based on three key steps: increasing water flow into the Everglades, reducing pollutants coming in, and developing strategies for dealing with future problems.

The first step—increasing water flow—will counteract some of the effects of decades of drainage by local communities. Its goal is to provide enough water to support the Everglades' aquatic and marsh organisms. The plan calls for restoring natural water flow as well as natural hydroperiods (seasonal increases and decreases in water flow). Its strategies include removal of over 390 km (240 miles) of inland levees, canals, and water control structures that have blocked this natural water movement.

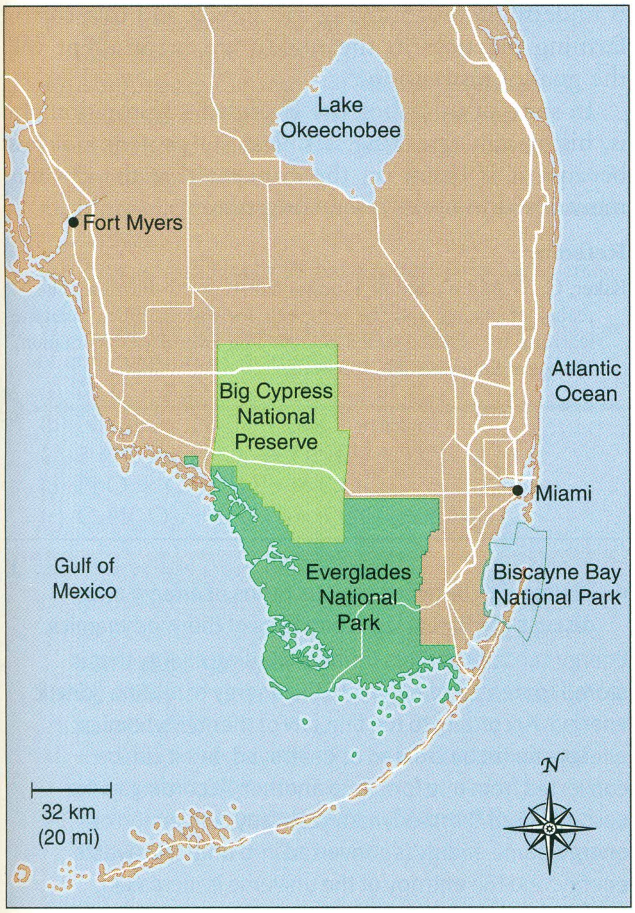


FIGURE 2.22 **The Florida Everglades Ecosystem.** This map shows the locations of the Florida Everglades, Lake Okeechobee, and the broader Everglades ecosystem, which includes Everglades and Biscayne Bay National Parks and Big Cypress National Preserve.

FIGURE 2.23 **River of grass.** The subtropical wetland portion of the Florida Everglades has been described as a river of grass because of the tall water-tolerant grasses that cover its surface.

Water conservation will also be a crucial part of reaching this goal. New water storage facilities and restored wetlands will capture and store water during rainy seasons for use during dry seasons, redirecting much of the 6.4 billion liters (1.7 billion gallons) of fresh water that currently flow to the ocean every day. About 80 percent of this fresh water will be redistributed back into the ecosystem via wetlands and aquifers. The remaining water will be used by cities and farms. The federal and state governments also hope to purchase nearby irrigated cropland and return it to a more natural state. In 2009, for example, the state of Florida purchased 29,000 ha (71,700 acres) of land from the United States Sugar Corporation, the first of a number of actions that will allow engineers to restore the natural flow of water from Lake Okeechobee into the Everglades. Florida is currently negotiating to purchase even more land from United States Sugar.

To achieve the second goal—reducing water pollution—local authorities will improve waste treatment facilities and place restrictions on the use of agricultural chemicals. Marshlands are particularly effective at absorbing nutrients and breaking down toxins. Landscape engineers have designed and built more than 21,000 ha (52,000 acres) of artificial marshes upstream of the Everglades to help clean water before it reaches Everglades National Park. Although not all of the region has seen water quality improvements, phosphorus concentrations in runoff from farms south of Lake Okeechobee are lower, meaning that fewer pollutants are reaching the Everglades.

The third goal—to plan for the possibility of future problems—requires an **adaptive management plan:** a strategy that provides flexibility so that managers can modify it as future changes occur. Adaptive management is an answer to scientific uncertainty. In a highly complex system such as the Everglades, any changes, however well intentioned, may have unexpected consequences. Management strategies must adapt to the actual results of the restoration plan as they occur. In addition, an adaptive management plan can be changed to meet new challenges as they come. One such challenge is global warming. As the climate warms, glaciers melt, and sea levels rise, much of the Everglades could be inundated by seawater, which would destroy freshwater habitat. Adaptive management essentially means paying attention to what works and adjusting your methods accordingly. The Everglades restoration plan will be adjusted along the way to take the results of ongoing observations into account, and it has put formal mechanisms in place to ensure that this will occur.

The Everglades plan has its critics. Some people are concerned that control of water flow and pollution will restrict the use of private property and affect economic development, possibly even harming the local economy. Yet other critics fear that the restoration project is underfunded or moving too slowly, and that current farming practices in the region are inconsistent with the goal of restoration.

In spite of its critics, the Everglades restoration plan is, historically speaking, a milestone project, not least because it is based on the concept that the environment is made up of interacting systems.

Reference

Kiker, C., W. Milon, and A. Hodges. 2001. South Florida: The reality of change and the prospects for sustainability. Adaptive learning for science-based policy: The Everglades restoration. *Ecological Economics* 37: 403–416.

KEY IDEAS REVISITED

- **Define *systems* within the context of environmental science.**

Environmental systems are sets of interacting components connected in such a way that changes in one part of the system affect the other parts. Systems exist at multiple scales, and a large system may contain smaller systems within it. Earth itself is a single interconnected system.

- **Explain the components and states of matter.**

Matter is composed of atoms, which are made up of protons, neutrons, and electrons. Atoms and molecules can interact in chemical reactions in which the bonds between particular atoms may change. Matter cannot be created or destroyed, but its form can be changed.

- **Distinguish between various forms of energy and discuss the first and second laws of thermodynamics.**

Energy can take various forms, including energy that is stored (potential energy) and the energy of motion (kinetic energy). According to the first law of thermodynamics, energy cannot be created or destroyed, but it can be converted from one form into another. According to the second law of thermodynamics, in any conversion of energy, some energy is converted into unusable waste energy, and the entropy of the universe is increased.

- **Describe the ways in which ecological systems depend on energy inputs.**

Individual organisms rely on a continuous input of energy in order to survive, grow, and reproduce. More organisms can live where more energy is available.

- **Explain how scientists keep track of inputs, outputs, and changes to complex systems.**

Systems can be open or closed to exchanges of matter, energy, or both. A systems analysis determines what goes into, what comes out of, and what has changed within a given system. Environmental scientists use systems analysis to calculate inputs to and outputs from a system and its rate of change. If there is no overall change, the system is in steady state. Changes in one input or output can affect the entire system.

- **Describe how natural systems change over time and space.**

Variation in environmental conditions, such as temperature or precipitation, can affect the types and numbers of organisms present. Short-term and long-term changes in Earth's climate also affect species distributions.

PREPARING FOR THE AP EXAM

MULTIPLE-CHOICE QUESTIONS

1. Which of the following statements about atoms and molecules is *correct?*
(a) The mass number of an element is always less than its atomic number.
(b) Isotopes are the result of varying numbers of neutrons in atoms of the same element.
(c) Ionic bonds involve electrons while covalent bonds involve protons.
(d) Inorganic compounds never contain the element carbon.
(e) Protons and electrons have roughly the same mass.

2. Which of the following does *not* demonstrate the law of conservation of matter?
(a) $CH_4 + 2\,O_2 \rightarrow CO_2 + 2\,H_2O$
(b) $NaOH + HCl \rightarrow NaCl + H_2O$
(c) $2\,NO_2 + H_2O \rightarrow HNO_3 + HNO_2$
(d) $PbO + C \rightarrow 2\,Pb + CO_2$
(e) $C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$

3. Pure water has a pH of 7 because
(a) its surface tension equally attracts acids and bases.
(b) its polarity results in a molecule with a positive and a negative end.
(c) its ability to dissolve carbon dioxide adjusts its natural pH.
(d) its capillary action attracts it to the surfaces of solid substances.
(e) its H^+ concentration is equal to its OH^- concentration.

4. Which of the following is *not* a type of organic biological molecule?
(a) Lipids
(b) Carbohydrates
(c) Salts
(d) Nucleic acids
(e) Proteins

5. A wooden log that weighs 1.00 kg is placed in a fireplace. Once lit, it is allowed to burn until there are only traces of ash, weighing 0.04 kg, left. Which of the following *best* describes the flow of energy?
(a) The potential energy of the wooden log was converted into the kinetic energy of heat and light.
(b) The kinetic energy of the wooden log was converted into 0.04 kg of ash.
(c) The potential energy of the wooden log was converted into 1.00 J of heat.
(d) Since the ash weighs less than the wooden log, matter was converted directly into energy.
(e) The burning of the 1.00 kg wooden log produced 0.96 kg of gases and 0.04 kg of ash.

6. Consider a power plant that uses natural gas as a fuel to generate electricity. If there are 10,000 J of chemical energy contained in a specified amount of natural gas, then the amount of electricity that could be produced would be
(a) greater than 10,000 J because electricity has a higher energy quality than natural gas.
(b) something less than 10,000 J, depending on the efficiency of the generator.
(c) greater than 10,000 J when energy demands are highest; less than 10,000 J when energy demands are lowest.
(d) greater than 10,000 J because of the positive feedback loop of waste heat.
(e) equal to 10,000 J because energy cannot be created or destroyed.

7. A lake that has been affected by acid rain has a pH of 4. How many more times acidic is the lake water than seawater? (See Figure 2.8 on page 34.)
(a) 4
(b) 10
(c) 100
(d) 1,000
(e) 10,000

8. An automobile with an internal combustion engine converts the potential energy of gasoline (44 MJ/kg) into the kinetic energy of the moving pistons. If the average internal combustion engine is 10 percent efficient and 1 kg of gasoline is combusted, how much potential energy is converted into energy to run the pistons?

(a) 39.6 MJ
(b) 20.0 MJ
(c) 4.4 MJ
(d) Depends on the capacity of the gas tank
(e) Depends on the size of the engine

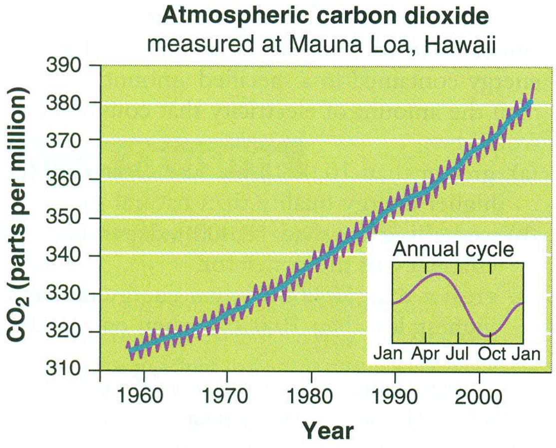
9. If the average adult woman consumes approximately 2,000 kcal per day, how long would she need to run in order to utilize 25 percent of her caloric intake, given that the energy requirement for running is 42,000 J per minute?

(a) 200 minutes
(b) 50 minutes
(c) 5 minutes
(d) 0.05 minutes
(e) 0.012 minutes

10. The National Hurricane Center studies the origins and intensities of hurricanes over the Atlantic and Pacific oceans and attempts to forecast their tracks, predict where they will make landfall, and assess what damage will result. Its systems analysis involves

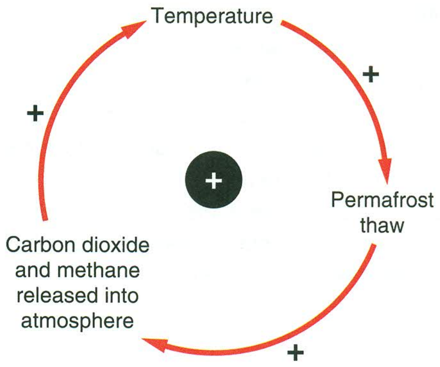
(a) changes within a closed system.
(b) inputs and outputs within a closed system.
(c) outputs only within an open system.
(d) inputs from a closed system and outputs in an open system.
(e) inputs, outputs, and changes within an open system.

11. Based on the graph below, which of the following is the *best* interpretation of the data?



(a) The atmospheric carbon dioxide concentration is in steady state.
(b) The output of carbon dioxide from the atmosphere is greater than the input into the atmosphere.
(c) The atmospheric carbon dioxide concentration appears to be decreasing.
(d) The input of carbon dioxide into the atmosphere is greater than the output from the atmosphere.
(e) The atmospheric carbon dioxide concentration will level off due to the annual cycle.

12. The diagram below represents which of the following concepts?



(a) A negative feedback loop, because melting of permafrost has a negative effect on the environment by increasing the amounts of carbon dioxide and methane in the atmosphere.
(b) A closed system, because only the concentrations of carbon dioxide and methane in the atmosphere contribute to the permafrost thaw.
(c) A positive feedback loop, because more carbon dioxide and methane in the atmosphere result in greater permafrost thaw, which releases more carbon dioxide and methane into the atmosphere.
(d) An open system that resists change and regulates global temperatures.
(e) Steady state, because inputs and outputs are equal.

13. Which of the following statements about the Comprehensive Everglades Restoration Plan is *not* correct?

(a) Human and natural systems interact because feedback loops lead to adaptations and changes in both systems.
(b) Water conservation will alter land uses and restore populations of aquatic and marsh organisms.
(c) Improvements in waste treatment facilities and restrictions on agricultural chemicals will reduce the nutrients and toxins in the water that reaches the Everglades.
(d) Adaptive management will allow for the modification of strategies as changes occur in this complex system.
(e) The Florida Everglades is a closed system that includes positive and negative feedback loops and is regulated as such.

14. Which of the following would represent a system in steady state?

I The birth rate of chameleons on the island of Madagascar equals their death rate.
II Evaporation from a lake is greater than precipitation and runoff flowing into the lake.
III The steady flow of the Colorado River results in more erosion than deposition of rock particles.

(a) I only
(b) II only
(c) III only
(d) I and II
(e) I and III

FREE-RESPONSE QUESTIONS

1. The atomic number of uranium-235 is 92, its half-life is 704 million years, and the radioactive decay of 1 kg of ^{235}U releases 6.7×10^{13} J. Radioactive material must be stored in a safe container or buried deep underground until its radiation output drops to a safe level. Generally, it is considered "safe" after 10 half-lives.
   - (a) Assume that a nuclear power plant can convert energy from ^{235}U into electricity with an efficiency of 35 percent, the electrical transmission lines operate at 90 percent efficiency, and fluorescent lights operate at 22 percent efficiency.
     - (i) What is the overall efficiency of converting the energy of ^{235}U into fluorescent light? (2 points)
     - (ii) How much energy from 1 kg of ^{235}U is converted into fluorescent light? (2 points)
     - (iii) Name one way in which you could improve the overall efficiency of this system. Explain how your suggestion would improve efficiency. (2 points)
   - (b) What are the first and second laws of thermodynamics? (2 points)
   - (c) How long would it take for the radiation from a sample of ^{235}U to reach a safe level? (2 points)

2. U.S. wheat farmers produce, on average, 3,000 kg of wheat per hectare. Farmers who plant wheat year after year on the same fields must add fertilizers to replace the nutrients removed by the harvested wheat. Consider a wheat farm as an open system.
   - (a) Identify two inputs and two outputs of this system. (4 points)
   - (b) Using one input to and one output from (a), diagram and explain one positive feedback loop. (2 points)
   - (c) Identify two adaptive management strategies that could be employed if a drought occurred. (2 points)
   - (d) Wheat contains about 2.5 kcal per gram, and the average U.S. male consumes 2,500 kcal per day. How many hectares of wheat are needed to support one average U.S. male for a year, assuming that 30 percent of his caloric intake is from wheat? (2 points)

MEASURING YOUR IMPACT

Bottled Water versus Tap Water A 2007 study traced the energy input required to produce bottled water in the United States. In addition to the energy required to make plastic bottles from PET (polyethylene terephthalate), energy from 58 million barrels of oil was required to clean, fill, seal, and label the water bottles. This is 2,000 times more than the amount of energy required to produce tap water.

In 2007, the population of the United States was 300 million people, and on average, each of those people consumed 114 L (30 gallons) of bottled water. The average 0.6 L (20-ounce) bottle of water cost $1.00. The average charge for municipal tap water was about $0.0004 per liter.

- (a) Complete the following table for the year 2007. Show all calculations.

Liters of bottled water consumed in 2007	Liters of bottled water produced per barrel of oil

- (b) How much energy (in barrels of oil) would be required to produce the amount of tap water equivalent to the amount of bottled water consumed in 2007? How many liters of tap water could be produced per barrel of oil?
- (c) Compare the cost of bottled water versus tap water per capita per year.
- (d) Identify and explain one output of the bottled water production and consumption system that could have a negative effect on the environment.
- (e) List two reasons for using tap water rather than bottled water.

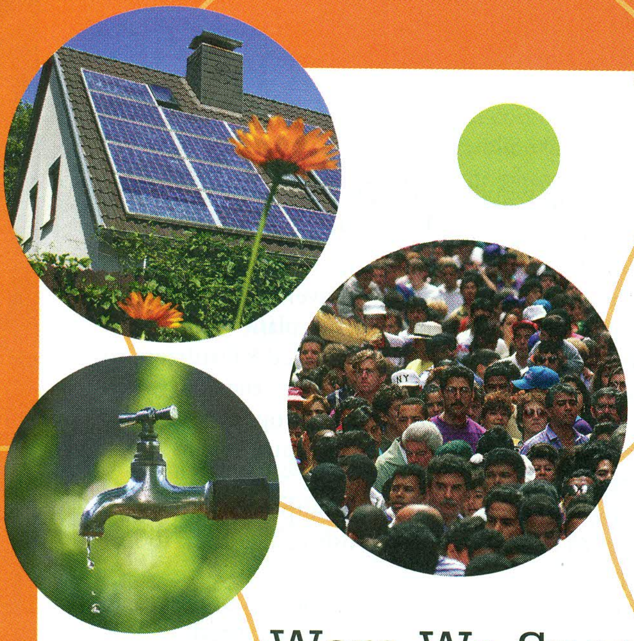
EXPLORING THE LITERATURE

Hart, J. 1996. *Storm Over Mono: The Mono Lake Battle and the California Water Future.* University of California Press.

Kendall, K. E., and J. E. Kendall. 2008. *Systems Analysis and Design.* 7th ed. Prentice Hall.

Meadows, D. 2008. *Thinking in Systems: A Primer.* Chelsea Green.

Moore, J. T. E. 2005. *Chemistry Made Simple.* Broadway Press.



science applied

Were We Successful in Halting the Growth of the Ozone Hole?

We rely on refrigeration to keep our foods safe and edible, and on air conditioning to keep us comfortable in hot weather. For many years, the same chemicals that made refrigeration and air conditioning possible were also used in a host of other consumer items, including aerosol spray cans and products such as Styrofoam. These chemicals, called chlorofluorocarbons, or CFCs, were considered essential to modern life, and producing them was a multibillion-dollar industry. CFCs were considered "safe" because they are both nontoxic and nonflammable.

Why do we need an ozone layer?

In the 1970s, scientists learned that CFCs might be responsible for destroying ozone in the upper atmosphere. This discovery led to great concern because a layer of ozone in the upper atmosphere protects us from high-energy ultraviolet (UV) radiation, which causes sunburns, skin cancer, and cataracts as well as environmental damage. In the 1980s, scientists reported an ozone "hole," or depletion of ozone, over Antarctica and documented dangerous thinning of the ozone layer elsewhere.

The nations of the world faced a critical choice: should they continue to produce and use CFCs, and risk further damage to the ozone layer and the resulting effects on people and natural systems, or should they reduce ozone depletion by discontinuing use of this important class of chemicals? In 1987, the majority of nations chose the latter course. As of this writing, most of the world has stopped using CFCs. But the choice at the time was a difficult one. What were the scientific findings that convinced nations to phase out CFCs, the economic consequences of this important decision, and finally, the impact of the CFC ban on the environment? Have we, indeed, protected the ozone layer?

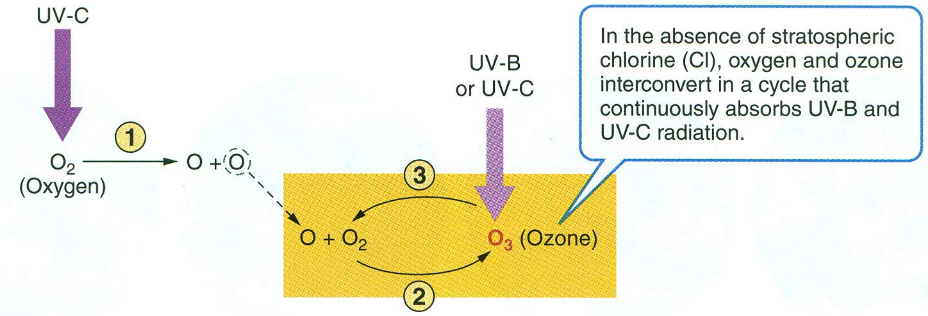
How do chlorofluorocarbons damage the ozone layer?

As we saw in Chapter 2, the Sun radiates energy at many different wavelengths, including the ultraviolet range. The ultraviolet wavelengths are further classified into three groups: UV-A, or low-energy ultraviolet radiation, and the shorter, higher-energy UV-B and UV-C wavelengths. UV radiation of all types can damage the tissues and DNA of living organisms. Exposure to UV-B radiation increases the risks of skin cancer and cataracts and suppresses the immune system. Exposure to UV-B is also harmful to the cells of plants and reduces their ability to convert sunlight into usable energy. UV-B exposure can therefore lead to crop losses and effects on entire biological communities. For example, losses of phytoplankton—the microscopic algae that form the base of many marine food chains—can harm fisheries.

Next we examine the chemistry of ozone production and how the introduction of chlorine atoms disturbs ozone's steady state in the stratosphere. Oxygen molecules (O_2) are common throughout Earth's atmosphere. When solar radiation hits O_2 in the stratosphere, 16 to 50 km (10–31 miles) above Earth's surface, a series of chemical reactions begins that produces a new molecule: ozone (O_3).

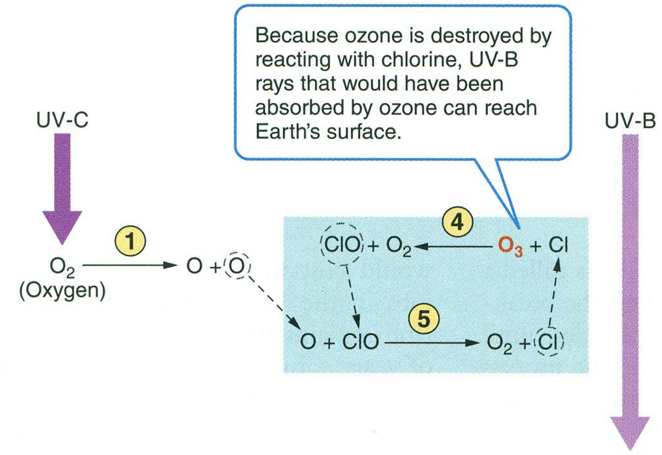
In the first step, UV-C radiation breaks the molecular bond holding an oxygen molecule together:

$$O_2 + \text{UV-C} \rightarrow O + O \qquad (1)$$



In the absence of stratospheric chlorine (Cl), oxygen and ozone interconvert in a cycle that continuously absorbs UV-B and UV-C radiation.

(a) Ozone production and cycling



Because ozone is destroyed by reacting with chlorine, UV-B rays that would have been absorbed by ozone can reach Earth's surface.

(b) Effect of chlorine on ozone

FIGURE SA1.1 **Oxygen-ozone cycles in the stratosphere.** Circled numbers refer to the numbered chemical reactions in the text.

This happens to only a few oxygen molecules at any given time. The vast majority of the oxygen in the atmosphere remains in the form O_2.

In the second step, a free oxygen atom (O) produced in reaction 1 encounters an oxygen molecule, and they form ozone. The simplified form of this reaction is written as follows:

$$O + O_2 \rightarrow O_3 \qquad (2)$$

Both UV-B and UV-C radiation can break a bond in this new ozone molecule, forming molecular oxygen and a free oxygen atom once again:

$$O_3 + \text{UV-B or UV-C} \rightarrow O_2 + O \qquad (3)$$

Thus the formation of ozone in the presence of sunlight and its subsequent breakdown is a cycle (FIGURE SA1.1) that can occur indefinitely as long as there is UV energy entering the atmosphere. Under normal conditions, the amount of ozone in the stratosphere remains at steady state.

However, certain chemicals can promote the breakdown of ozone, disrupting this steady state. Free chlorine (Cl) is one such chemical. The concern over CFCs began when atmospheric scientists realized that CFCs were introducing chlorine into the stratosphere. When chlorine is present, it can attach to an oxygen atom in an ozone molecule, thereby breaking the bond between that atom and the molecule and forming chlorine monoxide (ClO) and O_2:

$$O_3 + Cl \rightarrow ClO + O_2 \qquad (4)$$

Subsequently, the chlorine monoxide molecule reacts with a free oxygen atom, which pulls the oxygen from the ClO to produce free chlorine again:

$$ClO + O \rightarrow Cl + O_2 \qquad (5)$$

Looking at reactions 4 and 5 together, we see that chlorine starts out and ends up as a free Cl atom. In contrast, an ozone molecule and a free oxygen atom are converted into two oxygen molecules. A substance that

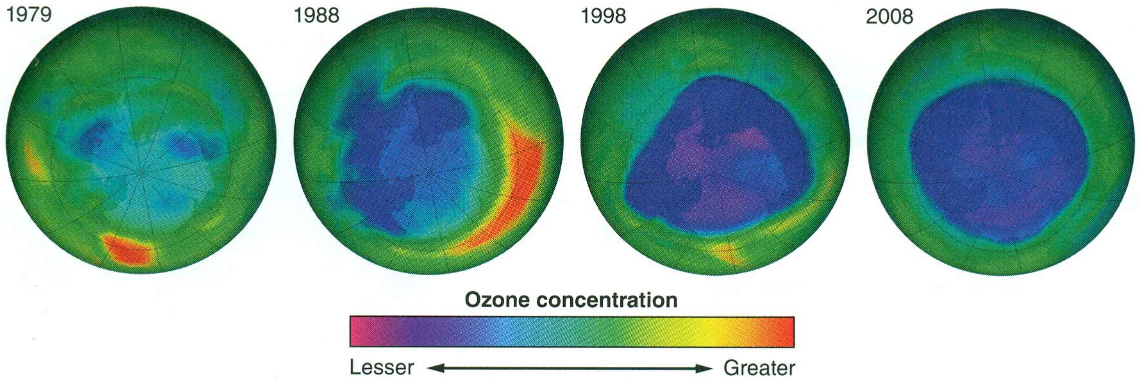


FIGURE SA1.2 **The ozone hole over time.** An area of decreased atmospheric ozone concentration has been forming during the Antarctic spring (September–December) every year since 1979. There has been a decrease in ozone to about one-third of its 1979 concentration.

aids a reaction but does not get used up itself is called a **catalyst.** A single chlorine atom can catalyze the breakdown of as many as 100,000 ozone molecules, until finally one chlorine atom finds another and the process is stopped. The ozone molecules are no longer available to absorb incoming UV-B radiation. As a result, the UV-B radiation can reach Earth's surface and cause biological harm.

How did nations address the ozone crisis?

In response to the findings described above, the U.S. Environmental Protection Agency banned the use of CFCs in most aerosol sprays in 1978. Policy makers deemed further actions to reduce CFC use too expensive.

By 1986, however, the political climate had changed dramatically. British scientists announced the discovery of a vast ozone "hole" forming seasonally over Antarctica (FIGURE SA1.2). This region of unusually low ozone concentrations had not been predicted by scientific models, and the idea of an unexpected hole in the ozone layer captured public attention. Moreover, two important reports appeared in 1985 and 1986, from the World Meteorological Organization and the EPA, that demonstrated an emerging scientific consensus on the magnitude of the ozone depletion problem. Finally, DuPont, the world's leading producer of CFCs, stated that CFC alternatives could be available within 5 years, given the right market conditions.

The issue remained contentious, however. In order to convert to CFC alternatives, many industries would need to be retrofitted with new equipment, and those industries were strongly opposed to the change. In 1987, a trade group called the CFC Alliance estimated that just stopping the *growth* of new CFC production would cost more than $1 billion and affect 700,000 jobs in the United States. In addition, because chlorine remains in the stratosphere for tens to hundreds of years, some argued that a reduction in CFCs would have minimal short-term benefits for the environment and would result in an improvement only after several decades, not justifying expensive changes now.

In spite of these objections, in 1987, 24 nations signed an agreement called the Montreal Protocol on Substances That Deplete the Ozone Layer. Those nations committed to taking concrete steps to cut the production of CFCs in half by the year 2000. As the scientific case against CFCs strengthened and the economic costs turned out to be less than had been projected, more nations joined the Montreal Protocol, and amendments added in 1990 and 1992 strengthened the treaty by calling for a complete phaseout of CFCs in developed countries by 1996.

Small amounts of CFCs continue to be used in developing countries, and certain agricultural chemicals and CFC replacements can also destroy ozone, although to a lesser degree than CFCs. However, because of the Montreal Protocol, CFC production worldwide had fallen to 2 percent of its peak value by 2004, and chlorine concentrations in the stratosphere are slowly decreasing. Scientists believe that stratospheric ozone depletion will decrease in subsequent decades as chlorine concentrations stabilize. New cases of skin cancer should eventually decrease as well, again after a significant time lapse due to the fact that some cancers take many years to appear.

The Montreal Protocol demonstrated that the manufacturers of products and the nations that used them were willing to make changes in manufacturing processes, and incur economic hardship, in order to protect the environment. Even more importantly, the agreement protects both human health and nonhuman organisms. A 1997 study by the Canadian government estimated that the Montreal Protocol would cost the global economy $235 billion (Canadian dollars) between 1987 and 2060, but would result in benefits worth twice that amount, even before considering the benefits to human health. For example, the study's economists estimated a global savings of almost $200 billion in agriculture because without the Montreal Protocol, the increased UV-B radiation would have damaged crop productivity. They also found that protection of the ozone layer avoided $238 billion in losses to global fisheries that depend on UV-B–sensitive phytoplankton as a food source. Because of its success, policy makers and environmental scientists view the Montreal Protocol as a model for future action on other international environmental problems such as climate change.

References

Kaniaru, D., ed. 2007. *The Montreal Protocol: Celebrating 20 Years of Environmental Progress—Ozone Layer and Climate Protection*. Cameron May.

Seinfeld, J. H., and S. N. Pandis. 2006. *Atmospheric Chemistry and Physics: From Air Pollution to Climate Change.* 2nd ed. Wiley.