Carbohydrates include simple sugars that are three to seven carbon atoms long. Glucose ($C_6H_{12}O_6$) fuels living cells and serves as a building block for complex carbohydrates, such as starch. Plants use starch to store energy, and animals eat plants to acquire starch. Plants and animals also use complex carbohydrates to build structure. Insects and crustaceans form hard shells from the carbohydrate chitin. Cellulose, the most abundant organic compound on Earth, is a complex carbohydrate found in the cell walls of leaves, bark, stems, and roots.

Lipids are a chemically diverse group of compounds, classified together because they do not dissolve in water. Lipids include fats and oils (for energy storage), phospholipids (for membranes), waxes (for structure), and steroids (for hormone production).

Organisms use cells to compartmentalize macromolecules

All living things are composed of **cells**, the most basic unit of organismal organization. Organisms range in complexity from single-celled bacteria to plants and animals that contain millions of cells. Cells vary greatly in size, shape, and function. Biologists classify organisms into two groups based on the structure of their cells. The cells of *eukaryotes* (plants, animals, fungi, and protists) contain a membrane-enclosed nucleus and various organelles that perform specific functions. *Prokaryotes* (bacteria and archaea) are generally single-celled, and their cells lack organelles and a nucleus.

Energy Fundamentals

Creating and maintaining organized complexity, whether of a cell, an organism, or an ecological system, requires energy. Energy is needed to organize matter into complex forms such as polymers, to build and maintain cellular structure, to power interactions among species, and to drive the geological forces that shape our planet. Energy is somehow involved in nearly every biological, chemical, and physical event.

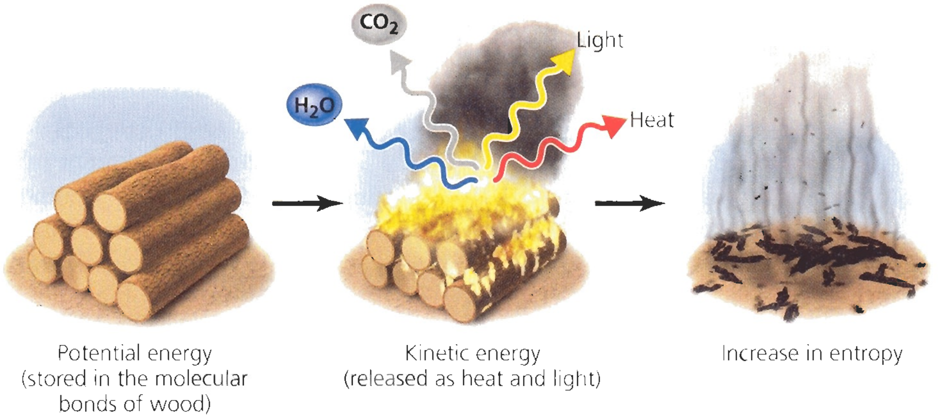
But what, exactly, is energy? An intangible phenomenon, **energy** is that which can change the position, physical composition, or temperature of matter. Scientists differentiate between two types of energy: **potential energy**, energy of position; and **kinetic energy**, energy of motion. Consider river water held behind a dam. By preventing water from moving downstream, the dam causes the water to accumulate potential energy. When the dam gates are opened, the potential energy is converted to kinetic energy, in the form of water's motion as it rushes downstream.

Such energy transfers take place at the atomic level every time a chemical bond is broken or formed. **Chemical energy** is potential energy held in the bonds between atoms. Bonds differ in their amounts of chemical energy, depending on the atoms they hold together. Converting a molecule with high-energy bonds (such as the carbon–carbon bonds of petroleum products) into molecules with lower-energy bonds (such as the bonds in water or carbon dioxide) releases energy by changing potential energy into kinetic energy and produces motion, action, or heat. Just as our automobile engines split the hydrocarbons of gasoline to release chemical energy and generate movement, our bodies split glucose molecules from our food for the same purpose.

Energy is always conserved, but it changes in quality

Although energy can change from one form to another, it cannot be created or lost. The total energy in the universe remains constant and thus is said to be conserved.

FIGURE 3.8 The burning of firewood demonstrates energy transfer leading from a more-ordered to a less-ordered state. This increase in entropy reflects the second law of thermodynamics.



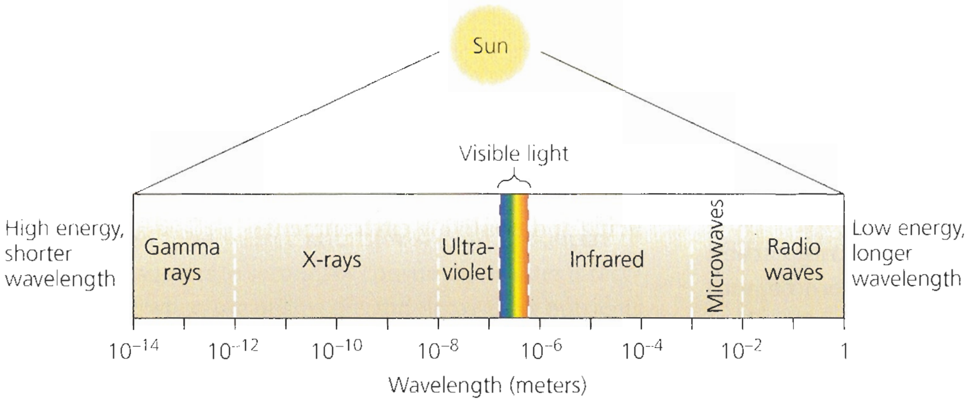


FIGURE 3.9 The sun emits radiation from many portions of the electromagnetic spectrum, and visible light makes up only a small proportion of this energy. Some radiation that reaches our planet is reflected back; some is absorbed by air, land, and water; and a small amount powers photosynthesis.

Scientists have dubbed this principle the **first law of thermodynamics**. The potential energy of the water behind a dam will equal the kinetic energy of its eventual movement down the riverbed. Similarly, burning converts the potential energy in a log of firewood to an equal amount of energy produced as heat and light.

Although the overall amount of energy is conserved in any process of energy transfer, the **second law of thermodynamics** states that the nature of energy will change from a more-ordered state to a less-ordered state, if no force counteracts this tendency. That is, systems tend to move toward increasing disorder, or *entropy*. For instance, after death every organism undergoes decomposition and loses its structure. A log of firewood—the highly organized and structurally complex product of many years of slow tree growth—transforms in the campfire to a residue of carbon ash, smoke, and gases such as carbon dioxide and water vapor, as well as the light and heat of the flame (Figure 3.8). With the help of oxygen, the complex biological polymers making up the wood are converted into a disorganized assortment of rudimentary molecules and heat and light energy.

Light energy from the sun powers most living systems

The energy that powers Earth's ecological systems comes primarily from the sun. The sun releases radiation from large portions of the electromagnetic spectrum, although our atmosphere filters much of this out and we see only some of this radiation as visible light (Figure 3.9).

The sun's radiation is used directly by some organisms to produce their own food. Such organisms, called **autotrophs** or **producers**, include green plants, algae, and bacteria called cyanobacteria. Autotrophs turn light energy from the sun into chemical energy through the process called **photosynthesis** (Figure 3.10). In photosynthesis, sunlight powers a series of chemical reactions that convert carbon dioxide and water into sugars, transforming low-quality energy from the sun into high-quality energy the organism can use. It is an example of moving toward a state of lower entropy, and as such it requires a substantial input of outside energy.

Photosynthesis occurs within cell organelles called *chloroplasts*, where the light-absorbing pigment *chlorophyll*

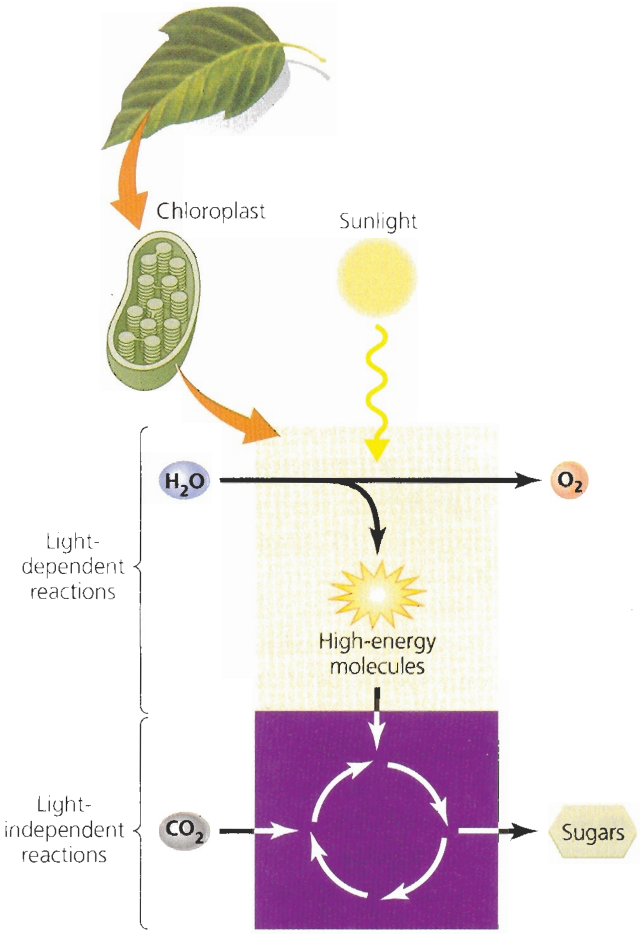


FIGURE 3.10 Autotrophs including plants, algae, and cyanobacteria use sunlight to convert carbon dioxide and water into sugars and oxygen in photosynthesis. Autotrophs provide themselves and the many heterotrophs that eat them with energy for life.

(which is what makes plants green) uses solar energy to initiate a series of chemical reactions called *light-dependent reactions.* During these reactions, water molecules are split, and they react to form hydrogen ions (H^+) and molecular oxygen (O_2), thus creating the oxygen that we breathe. The light-dependent reactions also produce small, high-energy molecules that are used to fuel a set of *light-independent reactions.* In these reactions, carbon atoms from carbon dioxide are linked together to manufacture sugars. Photosynthesis is a complex process, but the overall reaction can be summarized in the following equation:

$$\begin{array}{l} 6CO_2 + 6H_2O \\ + \text{the sun's energy} \end{array} \longrightarrow \begin{array}{l} C_6H_{12}O_6 + 6O_2 \\ \text{(sugar)} \end{array}$$

Thus in photosynthesis, green plants draw up water from the ground through their roots, absorb carbon dioxide from the air through their leaves, and harness sunlight. With these ingredients, they create sugars for their growth and maintenance and release as a by-product the oxygen that we, and all other animals, breathe.

Cellular respiration releases chemical energy

The chemical energy created by photosynthesis can later be used by organisms in the process known as **cellular respiration**. To release the chemical energy of glucose, cells use oxygen to convert glucose back into its original starting materials, water and carbon dioxide. The energy released during this process is used to form chemical bonds or to perform other tasks within cells. The net equation for cellular respiration is the exact opposite of that for photosynthesis:

$$\begin{array}{l} C_6H_{12}O_6 + 6O_2 \\ \text{(sugar)} \end{array} \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

However, the energy gained per glucose molecule in respiration is only two-thirds of the energy input per glucose molecule in photosynthesis—a prime example of the second law of thermodynamics in action. The extraction of energy from glucose through respiration occurs in the autotrophs that created the glucose and also in the animals that obtain glucose by consuming autotrophs. Organisms that consume autotrophs are called **heterotrophs**, or **consumers**, and include most animals, as well as the fungi and microbes that decompose organic matter. In most ecological systems, plants, algae, or cyanobacteria form the base of a food chain through which energy passes to heterotrophs (▸ pp. 101–102).

How Environmental Systems Work

Let's now apply our knowledge of chemistry and energy to see how energy, matter, and nutrients cycle through the living and nonliving environment.

Ecosystems are systems of interacting living and nonliving entities

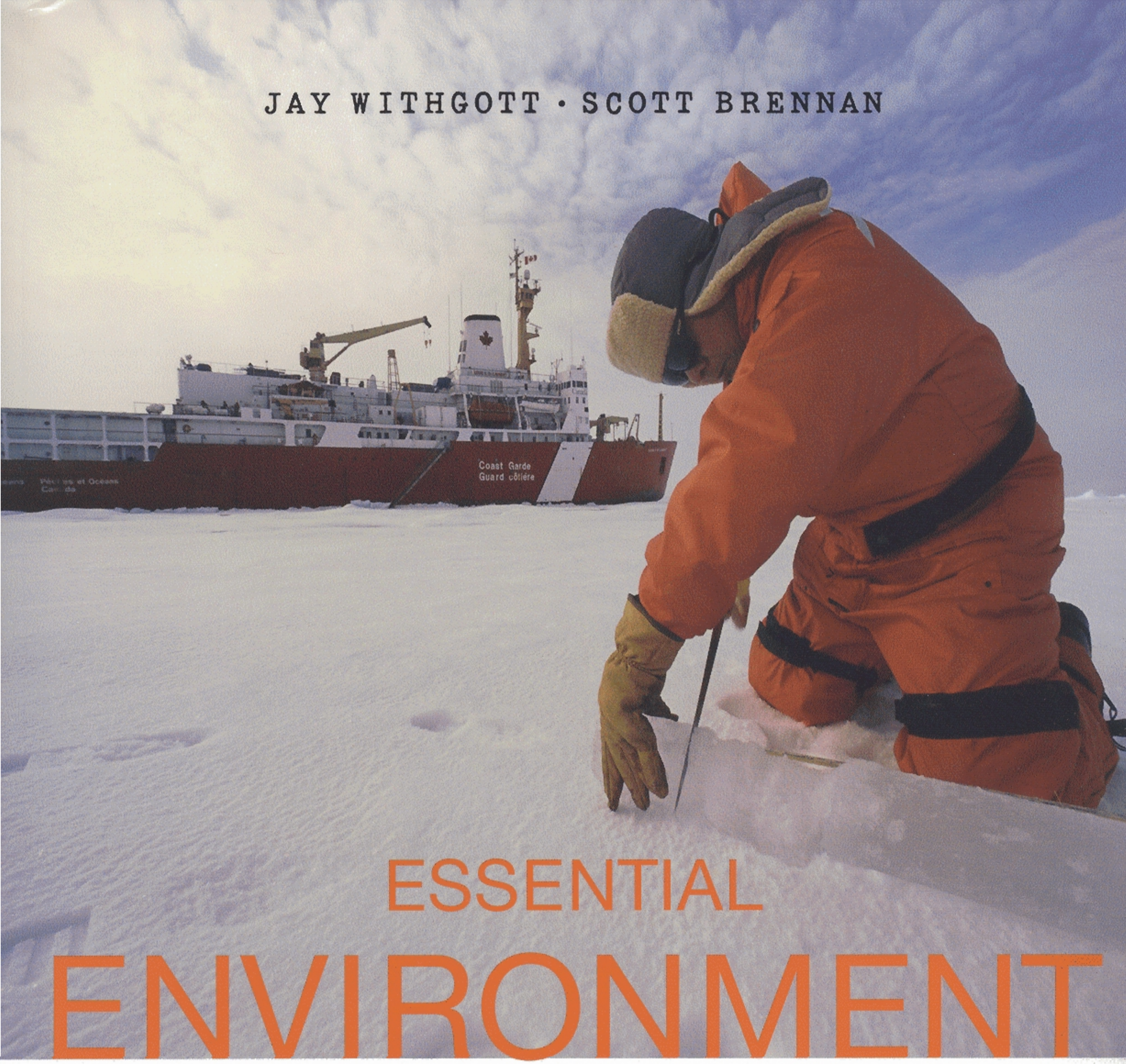
An **ecosystem** consists of all organisms and nonliving entities that occur and interact in a particular area at the same time. Animals, plants, air, water, soil, nutrients—all these and more help comprise ecosystems. An ecosystem can be as small as an ephemeral puddle of water where brine shrimp and tadpoles feed on algae and detritus with mad abandon as the pool dries up. Or an ecosystem might be as large as a lake or a forest. For some purposes, scientists even view the entire planet as a single all-encompassing ecosystem. The term is most often used, however, to refer to systems of moderate geographic extent with somewhat discrete boundaries. For example, the salt marshes that line the outer delta of the Mississippi River where its waters mix with those of the Gulf of Mexico may be classified as an ecosystem.

Ecosystems that physically abut one another may interact extensively. For instance, coastal dunes, the ocean, and the lagoon or salt marsh between them all interact, as do forests and prairie where they converge. Areas where ecosystems meet may consist of transitional zones called *ecotones,* in which elements of each ecosystem mix. Because of this mixing, ecologists sometimes find it useful to view these systems at a larger landscape scale that focuses on geographic areas that include multiple ecosystems. Such a broad-scale approach, often called *landscape ecology,* is important in studying birds that migrate between continents, for example, or fish, such as salmon, that move between marine and freshwater ecosystems.

Weighing the Issues: Ecosystems Where You Live

Think about the area where you live. How would you describe this area's ecosystems? How do these systems interact with one another? If one ecosystem were greatly disturbed (say, if a wetland or forest were replaced by a shopping mall), what impacts might that have on nearby natural systems?

JAY WITHGOTT · SCOTT BRENNAN



ESSENTIAL ENVIRONMENT

THE SCIENCE BEHIND THE STORIES

SECOND EDITION