3 Matter, Energy, and Life

▲Chesapeake Bay's ecosystem supports fisheries, recreation, and communities. But the estuary is an ecosystem out of balance.

Learning Outcomes

After studying this chapter, you should be able to:

3.1 Describe matter, elements, and molecules and give simple examples of the role of four major kinds of organic compounds in living cells.

3.2 Define energy and explain how thermodynamics regulates ecosystems.

3.3 Understand how living organisms capture energy and create organic compounds.

3.4 Define species, populations, communities, and ecosystems, and summarize the ecological significance of trophic levels.

3.5 Understand pathways in the water, carbon, nitrogen, sulfur, and phosphorus cycles.

"When one tugs at a single thing in nature, he finds it attached to the rest of the world."

– John Muir

CASE STUDY

Chesapeake Bay: How Do We Improve on a C−?

Each year Chesapeake Bay, the largest estuary in the United States, gets a report card, just as you do at the end of a semester. Like your report card, this one summarizes several key performance measures. Unlike your grades, the bay's grades are based on measures such as water clarity, oxygen levels, health of sea grass beds, and the condition of microscopic plankton community. These factors reflect overall stability of fish and shellfish populations, critical to the region's ecosystems and economy. Since record keeping began, the bay's performance has been poor, with scores hovering between 35 and 57 out of 100, and an average grade of low C. The main reason for the bad grades? Excessive levels of nitrogen and phosphorus, two common life-supporting elements that have destabilized the ecosystem.

Chesapeake Bay's watershed is a vast and complex system, with over 17,600 km (11,000 mi) of tidal shoreline in six states, and a population of 20 million people. Approximately 100,000 streams and rivers drain into the bay. All these streams carry runoff from forests, farmlands, cities, and suburbs from as far away as New York (fig. 3.1*a*).

The system has consistently bad grades, but it's clearly worth saving. Even in its impaired state, the bay provides 240 million kg (500 million lb) of seafood every year. It supports fishing and recreational economies worth $33 billion a year. But this is just a fraction of what it should be. The bay once provided abundant harvests of oysters, blue crabs, rockfish, white perch, shad, sturgeon, flounder, eel, menhaden, alewives, and soft-shell clams. Overharvesting, disease, and declining ecosystem productivity have decimated fisheries. Blue crabs are just above population survival levels. The oyster harvest, which was 15 to 20 million bushels per year in the 1890s, has declined to less than 1 percent of that amount. According to the Environmental Protection Agency (EPA), the bay should support more than twice the fish, crabs, and oysters that are there today. Human health is also at risk. After heavy rainfall, people are advised to stay out of the water for 48 hours, to avoid contamination from sewer overflows and urban and agricultural runoff.

The principal problem is simply excessive levels of nitrogen and phosphorus. These two elements are essential for life, but the system is overloaded by excess loads from farm fields, livestock manure, urban streets, suburban lawn fertilizer, the legal discharges of over 3,000 sewage treatment plants, and half a million aging household septic systems. Air pollution from cars, power plants, and factories also introduce nitrogen to the bay (fig. 3.1*b*). Sediment is also a key issue: it washes in from fields and streets, smothers eelgrass beds, and blocks sunlight, further reducing photosynthesis in the bay.

Just as too many donuts are bad for you, an excessive diet of nutrients is bad for an estuary. Excess nutrients fertilize superabundant growth of algae, which further blocks sunlight and reduces photosynthesis and oxygen levels in the bay. Lifeless, oxygen-depleted areas result. Fish, oysters, and crabs die off. These algal blooms in nutrient-enriched waters are increasingly common in bays and estuaries worldwide.

Progress has been discouragingly slow for decades, but in 2010 the EPA finally addressed the problem seriously, complying with its charge from Congress (under the Clean Water Act) to protect the bay. Where piecemeal, mostly voluntary efforts by individual states had long failed to improve the Chesapeake's report cards, the EPA brought all neighboring states to the negotiating table. Total maximum daily loads (TMDLs) for nutrients and sediments were established, and states were given freedom to decide how to meet their share of nitrogen reductions. But the EPA has legal authority from the Clean Water Act to enforce reductions. The aim is to cut

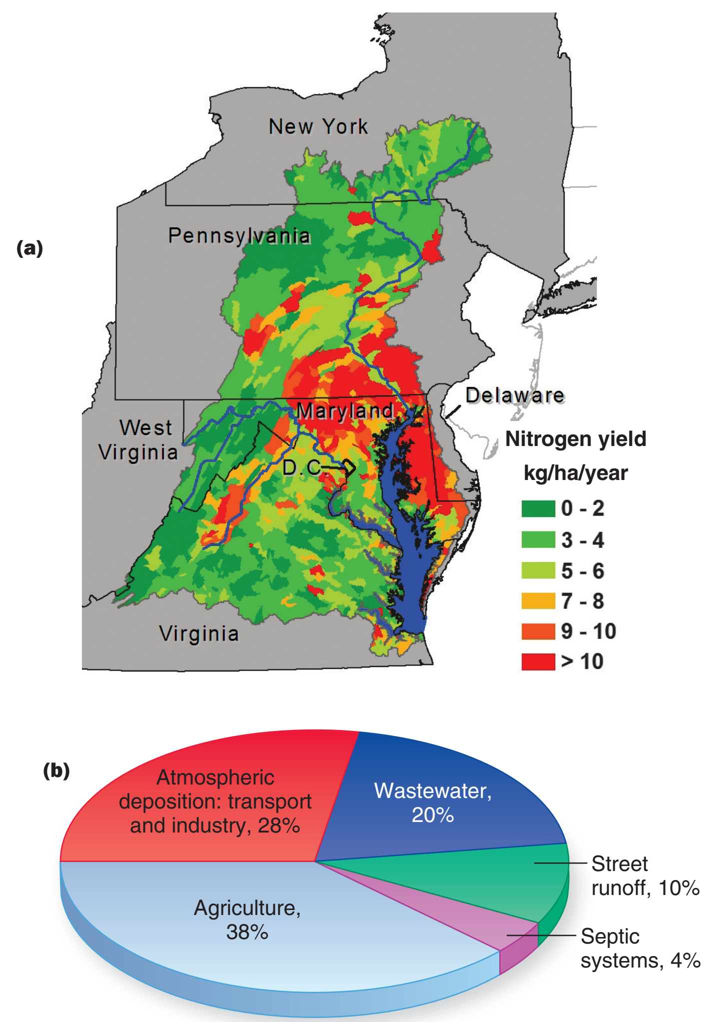

FIGURE 3.1 America's largest and richest estuary, Chesapeake Bay (shown in blue) suffers from pollutants from six states (a), and many sources (b).
Data sources: *USGS, EPA 2010.*

nitrogen levels by 25 percent, phosphorus by 24 percent, and sediment by 20 percent. The nitrogen target of 85 million kg (186 million lb) per year is still 4–5 times greater than would be released by an undisturbed watershed, but it's a huge improvement.

States from Virginia to New York have chosen their own strategies to meet limits. Maryland plans to capture and sell nitrogen and phosphorus from chicken manure. New York promises better urban wastewater treatment. Pennsylvania is strengthening soil conservation efforts to retain nutrients on farmland. Together, over time, these changes may rescue this magnificent estuary.

Chesapeake Bay has long been a symbol of the intractable difficulty of managing large, complex systems. Progress has required better understanding of several issues: the integrated functioning of the uplands and the waterways, the interdependence of the diverse human communities and economies that depend on the bay, and the pathways of nitrogen and phosphorus through an ecosystem.

Environmental scientists have led the way to the EPA's solution with years of ecosystem research and data collection. Through their efforts, and with EPA leadership, Chesapeake Bay could become the largest, and perhaps the most broadly beneficial, ecosystem restoration ever attempted in the United States. In this chapter we'll examine how these and other elements move through systems, and why they are important. Understanding these basic ideas will help you explain functioning of many different systems, including Chesapeake Bay, your local ecosystem, even your own body.

3.1 Elements of Life

- *From living organisms to ecosystems, life can be understood in terms of the movement of matter and energy.*
- *To understand how matter and energy cycle through living things, we must understand how atoms bond together to form compounds.*
- *Carbon-based ("organic") compounds are the foundation of organisms.*

The accumulation and transfer of energy and nutrients allows living systems, including yourself, to exist. These processes tie together the parts of an ecosystem—or an organism. In this chapter we'll introduce a number of concepts that are essential to understanding how living things function in their environment. These concepts include fundamental ideas of matter and energy, the ways organisms acquire and use energy, and the nature of chemical elements. We then apply these ideas to feeding relationships among organisms—the ways that energy and nutrients are passed from one living thing to another. In other words, we'll trace components from atoms to elements to compounds to cells to organisms to ecosystems.

Atoms, elements, and compounds

Everything that takes up space and has mass is **matter.** Matter exists in four distinct states, or phases—solid, liquid, gas, and plasma—which vary in energy intensity and the arrangement of particles that make up the substance. Water, for example, can exist as ice (solid), as liquid water, or as water vapor (gas). The fourth phase, plasma, occurs when matter is heated so intensely that electrons are released and particles become ionized (electrically charged). We can observe plasma in the sun, lightning, and very hot flames.

Under ordinary circumstances, matter is neither created nor destroyed; rather, it is recycled over and over again. The molecules that make up your body may contain atoms that once were part of the body of a dinosaur. Most certainly you contain atoms that were part of many smaller prehistoric organisms. This is because chemical elements are used and reused by living organisms. Matter is transformed and combined in different ways, but it doesn't disappear; everything goes somewhere. This idea is known as the principle of **conservation of matter.**

How does this principle apply to environmental science? It explains how components of environmental systems are intricately connected. From Chesapeake Bay to your local ecosystem to your own household, all matter comes from somewhere, and all waste goes somewhere. Pause to consider what you have eaten, used, or bought today. Then think of where those materials will go when you are done with them. You are intricately tied to both the sources and the destinations of everything you use. This is a useful idea for us as residents of a finite world. Ultimately, when we throw away our disposable goods, they don't really go "away," they just go somewhere else, to stay there for a while and then move on.

Matter consists of **elements,** which are substances that cannot be broken down into simpler forms by ordinary chemical reactions. Each of the 122 known elements (92 natural, plus 30 created under special conditions) has distinct chemical characteristics. Just four elements—oxygen, carbon, hydrogen, and nitrogen—are responsible for more than 96 percent of the mass of most living organisms. See if you can find these four elements in the periodic table of the elements at the end of this book.

Atoms are the smallest particles that exhibit the characteristics of an element. Atoms are composed of positively charged protons, negatively charged electrons, and electrically neutral neutrons. Protons and neutrons, which have approximately the same mass, are clustered in the nucleus in the center of the atom

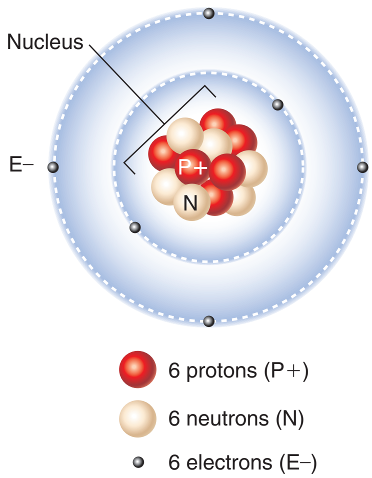

FIGURE 3.2 As difficult as it may be to imagine when you look at a solid object, all matter is composed of tiny, moving particles, separated by space and held together by energy. It is hard to capture these dynamic relationships in a drawing. This model represents carbon-12, with a nucleus of six protons and six neutrons; the six electrons are represented as a fuzzy cloud of potential locations rather than as individual particles.

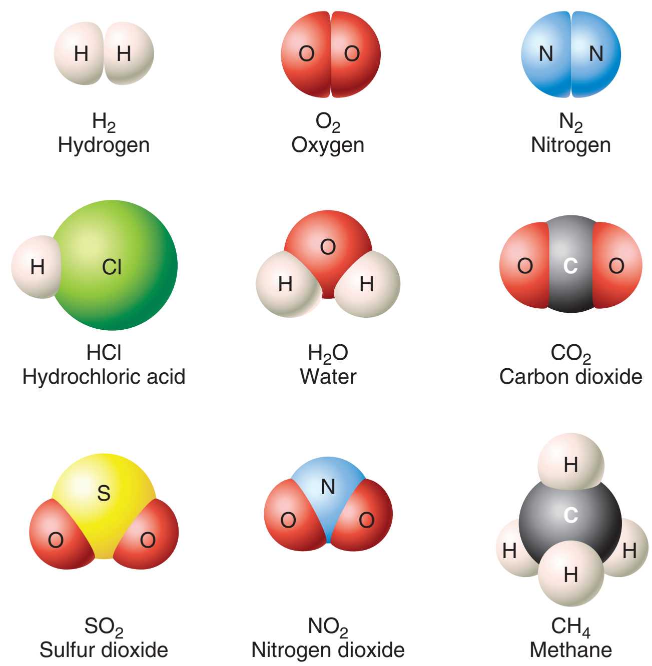

FIGURE 3.3 These common molecules, with atoms held together by covalent bonds, are important components of the atmosphere or are important pollutants.

(fig. 3.2). Electrons, which are tiny in comparison to the other particles, orbit the nucleus at the speed of light.

Each element has a characteristic number of protons per atom, called its **atomic number.** Each element also has a characteristic atomic mass, which is the sum of protons and neutrons (each having a mass of about 1). However, the number of neutrons can vary slightly. Forms of an element that differ in atomic mass are called **isotopes.** For example, hydrogen (H) is the lightest element, and normally it has just one proton and one electron (and no neutrons) and an atomic mass of 1. A small percentage of hydrogen atoms also have a neutron in the nucleus, which gives those atoms an atomic mass of 2 (one proton + one neutron). We call this isotope deuterium (^{2}H). An even smaller percentage of natural hydrogen called tritium (^{3}H) has one proton plus two neutrons. Oxygen atoms can also have one or two extra neutrons, making them the isotopes ^{17}O or ^{18}O, instead of the normal ^{16}O.

This difference is interesting to an environmental scientist. Water (H_2O) containing heavy ^{18}O generally evaporates most easily in hot climates, so we can detect ancient climate conditions by examining the abundance of ^{18}O in air bubbles trapped in ancient ice cores (chapter 15). Some isotopes are unstable—that is, they spontaneously emit electromagnetic energy or subatomic particles, or both. Radioactive waste and nuclear energy involve unstable isotopes of elements such as uranium and plutonium (chapters 19, 21).

Chemical bonds hold molecules together

Atoms often join to form **compounds,** or substances composed of different kinds of atoms (fig. 3.3). A pair or group of atoms that can exist as a single unit is known as a **molecule.** Some elements commonly occur as molecules, such as molecular oxygen (O_2) or molecular nitrogen (N_2), and some compounds can exist as molecules, such as glucose ($C_6H_{12}O_6$). In contrast to these molecules, sodium chloride (NaCl, table salt) is a compound that cannot exist as a single pair of atoms. Instead it occurs in a solid mass of Na and Cl atoms or as two ions, Na^+ and Cl^-, dissolved in solution. Most molecules consist of only a few atoms. Others, such as proteins and nucleic acids, discussed below, can include millions or even billions of atoms.

When ions with opposite charges form a compound, the electrical attraction holding them together is an *ionic bond.* Sometimes atoms form bonds by *sharing* electrons. For example, two hydrogen atoms can bond by sharing a pair of electrons—they orbit the two hydrogen nuclei equally and hold the atoms together. Such electron-sharing bonds are known as *covalent bonds.* Carbon (C) can form covalent bonds simultaneously with four other atoms, so carbon can create complex structures such as sugars and proteins. Atoms in covalent bonds do not always share electrons evenly. An important example in environmental science is the covalent bonds in water (H_2O). The oxygen atom attracts the shared electrons more strongly than do the two hydrogen atoms. Consequently, the hydrogen portion of the molecule has a slight positive charge, while the oxygen has a slight negative charge. These charges create a mild attraction between water molecules, so that water tends to be somewhat cohesive. This fact helps explain some of the remarkable properties of water (Exploring Science, p. 52).

When an atom gives up one or more electrons, we say it is *oxidized* (because it is very often oxygen, an abundant and highly reactive element, that takes the electron). When an atom gains electrons, we say it is *reduced.* Oxidation and reduction reactions are necessary for life: Oxidation of sugar and starch molecules, for example, is an important part of how you gain energy from food.

Forming bonds usually releases energy. Breaking bonds generally requires energy. Think of this in burning wood: carbon-rich organic compounds such as cellulose are *broken*, which requires energy; at the same time, oxygen from the air *forms* bonds with carbon from the wood, making CO_2. In a fire, more energy is produced than is consumed, and the net effect is that it feels hot to us.

EXPLORING SCIENCE

A "Water Planet"

If travelers from another solar system were to visit our lovely, cool, blue planet, they might call it Aqua rather than Terra because of its outstanding feature: the abundance of streams, rivers, lakes, and oceans of liquid water. Our planet is the only place we know where water exists as a liquid in any appreciable quantity. Water covers nearly three-fourths of the earth's surface and moves around constantly via the hydrologic cycle (discussed in chapter 15) that distributes nutrients, replenishes freshwater supplies, and shapes the land. Water makes up 60 to 70 percent of the weight of most living organisms. It fills cells, giving form and support to tissues. Among water's unique, even serendipitous qualities are the following:

1. Water molecules are polar: they have a slight positive charge on one side and a slight negative charge on the other side. Therefore, water readily dissolves polar or ionic substances, including sugars and nutrients, and carries materials to and from cells.
2. Water is the only inorganic substance that normally exists as a liquid at temperatures suitable for life. Most substances exist as either a solid or a gas, with only a very narrow liquid temperature range. Organisms synthesize organic compounds such as oils and alcohols that remain liquid at ambient temperatures and are therefore extremely valuable to life, but the original and predominant liquid in nature is water.
3. Water molecules are cohesive: they hold together tenaciously. You have experienced this property if you have ever done a belly flop off a diving board. Water has the highest surface tension of any common, natural liquid. Water also adheres to surfaces. As a result, water is subject to *capillary action:* it can be drawn into small channels. Without capillary action, movement of water and nutrients into groundwater reservoirs and through living organisms might not be possible.
4. Water is unique in that it expands when it crystallizes. Most substances shrink as they change from liquid to solid. Ice floats because it is less dense than liquid water. When temperatures fall below freezing, the surface layers of lakes, rivers, and oceans cool faster and freeze before deeper water. Floating ice then insulates underlying layers, keeping most water bodies liquid (and aquatic organisms alive) throughout the winter in most places. Without this feature, many aquatic systems would freeze solid in winter.
5. Water has a high heat of vaporization: it takes a great deal of heat to convert from liquid to vapor. Consequently, evaporating water is an effective way for organisms to shed excess heat. Many animals pant or sweat to moisten evaporative cooling surfaces. Why do you feel less comfortable on a hot, humid day than on a hot, dry day? Because the water vapor–laden air inhibits the rate of evaporation from your skin, thereby impairing your ability to shed heat.
6. Water also has a high specific heat: a great deal of heat is absorbed before it changes temperature. The slow response of water to temperature change helps moderate global temperatures, keeping the environment warm in winter and cool in summer. This effect is especially noticeable near the ocean, but it is important globally.

All these properties make water a unique and vitally important component of the ecological cycles that transfer matter and energy and that make life on earth possible.

Generally, some energy input (activation energy) is needed to start these reactions. In your fireplace, a match might provide the needed activation energy. In your car, a spark from the battery provides activation energy to initiate the oxidation (burning) of gasoline.

Ions react and bond to form compounds

Atoms frequently gain or lose electrons, acquiring a negative or positive electrical charge. Charged atoms (or combinations of atoms) are called **ions.** Negatively charged ions (with one or more extra electrons) are *anions.* Positively charged ions are *cations.* A hydrogen (H) atom, for example, can give up its sole electron to become a hydrogen ion (H^+). Chlorine (Cl) readily gains electrons, forming chlorine ions (Cl^-).

Substances that readily give up hydrogen ions in water are known as **acids.** Hydrochloric acid, for example, dissociates in water to form H^+ and Cl^- ions. In later chapters, you may read about acid rain (which has an abundance of H^+ ions), acid mine drainage, and many other environmental problems involving acids. In general, acids cause environmental damage because the H^+ ions react readily with living tissues (such as your skin or tissues of fish larvae) and with nonliving substances (such as the limestone on buildings, which erodes under acid rain).

Substances that readily bond with H^+ ions are called **bases** or alkaline substances. Sodium hydroxide (NaOH), for example, releases hydroxide ions (OH^-) that bond with H^+ ions in water. Bases can be highly reactive, so they also cause significant environmental problems. Acids and bases can also be essential to living

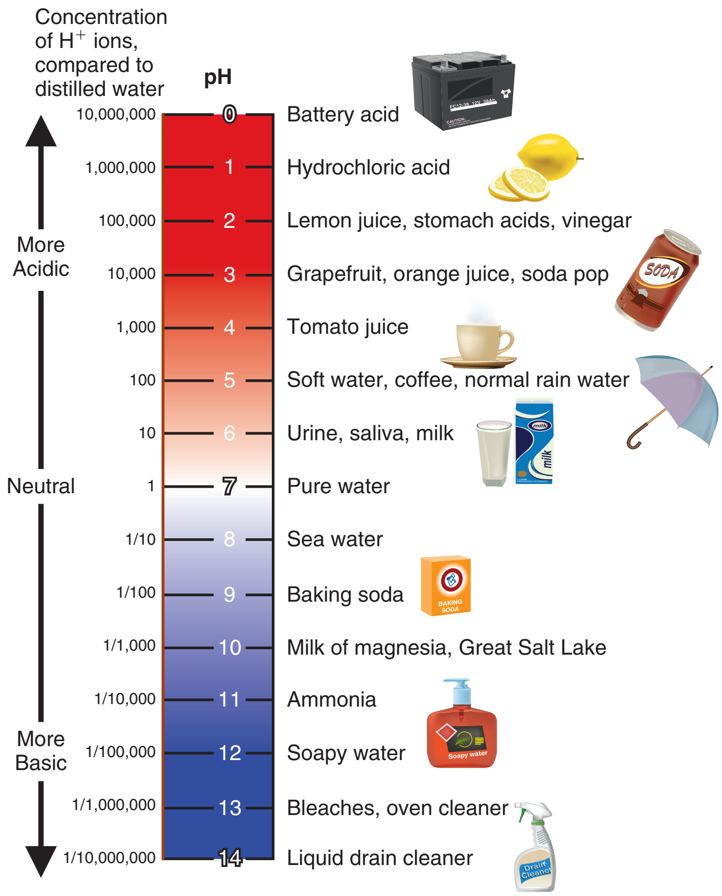

FIGURE 3.4 The pH scale. The numbers represent the negative logarithm of the hydrogen ion concentration in water. Alkaline (basic) solutions have a pH greater than 7. Acids (pH less than 7) have high concentrations of reactive H^+ ions.

things: The acids in your stomach dissolve food, for example, and acids in soil help make nutrients available to growing plants.

We describe the strength of an acid and base by its **pH,** the negative logarithm of its concentration of H^+ ions (fig. 3.4). Acids have a pH below 7; bases have a pH greater than 7. A solution of exactly pH 7 is "neutral." Because the pH scale is logarithmic, pH 6 represents *ten times* more hydrogen ions in solution than pH 7.

A solution can be neutralized by adding buffers—substances that accept or release hydrogen ions. In the environment, for example, alkaline rock can buffer acidic precipitation, decreasing its acidity. Lakes with acidic bedrock, such as granite, are especially vulnerable to acid rain because they have little buffering capacity.

Quantitative Reasoning

The pH scale shows availability of reactive hydrogen ions (H^+) in a liquid. The scale is logarithmic, so milk has 10 times as many H^+ ions as pure water, for a given volume. How many more H^+ ions does normal rain have, compared to pure water? Soda pop? Vinegar? Is sea water more acidic or more basic than pure water?

Organic compounds have a carbon backbone

Organisms use some elements in abundance, others in trace amounts, and others not at all. Certain vital substances are concentrated within cells, while others are actively excluded. Carbon is a particularly important element because chains and rings of carbon atoms form the skeletons of **organic compounds,** the material of which biomolecules, and therefore living organisms, are made.

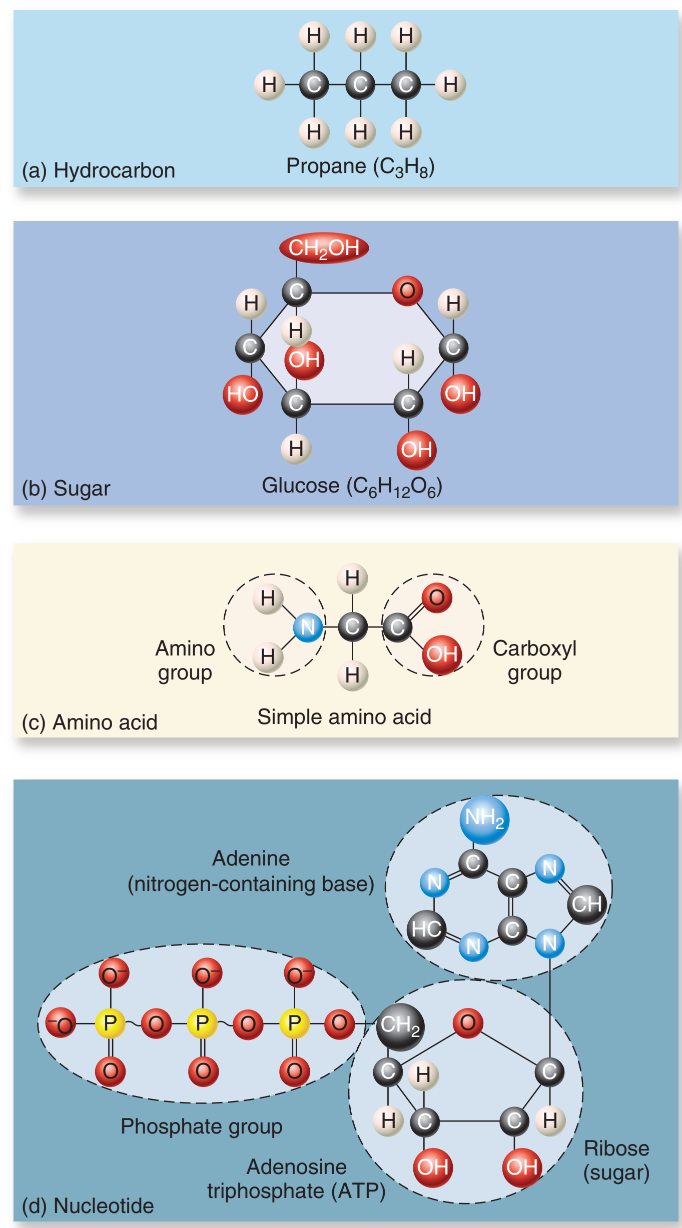

FIGURE 3.5 The four major groups of biologically important organic molecules are based on repeating subunits of these carbon-based structures. Basic structures are shown for (a) butyric acid (a building block of lipids) and a hydrocarbon, (b) a simple carbohydrate, (c) a protein, and (d) a nucleotide (a component of nucleic acids).

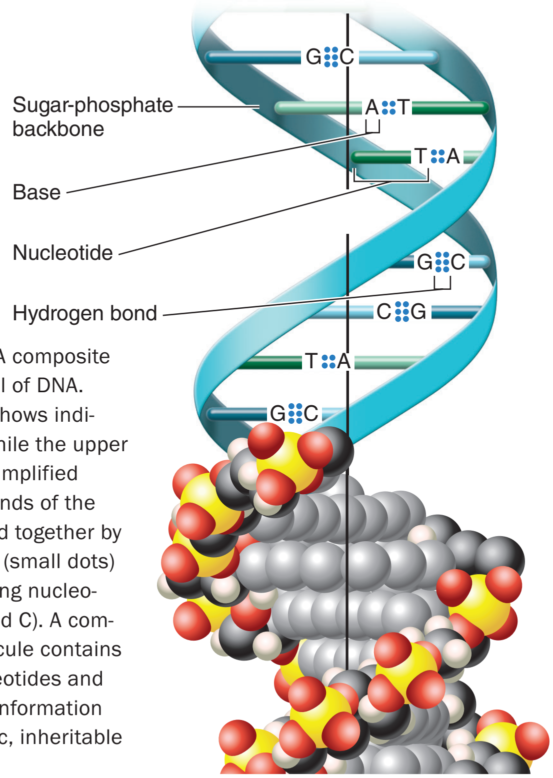

FIGURE 3.6 A composite molecular model of DNA. The lower part shows individual atoms, while the upper part has been simplified to show the strands of the double helix held together by hydrogen bonds (small dots) between matching nucleotides (A, T, G, and C). A complete DNA molecule contains millions of nucleotides and carries genetic information for many specific, inheritable traits.

There are four major categories of organic compounds in living things ("bio-organic compounds"): lipids, carbohydrates, proteins, and nucleic acids. Lipids (including fats and oils) store energy for cells, and they provide the core of cell membranes and other structures. Lipids do not readily dissolve in water, and their basic structure is a chain of carbon atoms with attached hydrogen atoms. This structure makes them part of the family of hydrocarbons (fig. 3.5*a*). Carbohydrates (including sugars, starches, and cellulose) also store energy and provide structure to cells. Like lipids, carbohydrates have a basic structure of carbon atoms, but hydroxyl (OH) groups replace half the hydrogen atoms in their basic structure, and they usually consist of long chains of sugars. Glucose (fig. 3.5*b*) is an example of a very simple sugar.

Proteins are composed of chains of subunits called amino acids (fig. 3.5*c*). Folded into complex three-dimensional shapes, proteins provide structure to cells and are used for countless cell functions. Most enzymes, such as those that release energy from lipids and carbohydrates, are proteins. Proteins also help identify disease-causing microbes, make muscles move, transport oxygen to cells, and regulate cell activity.

Nucleotides are complex molecules made of a five-carbon sugar (ribose or deoxyribose), one or more phosphate groups, and an organic nitrogen-containing base called either a purine or pyrimidine (fig. 3.5*d*). Nucleotides serve many functions. They carry information between cells, tissues, and organs. They are sources of energy for cells. They also form long chains called *r*ibo*n*ucleic *a*cid (RNA) or ***d*eoxyribo*n*ucleic *a*cid (DNA)** that are essential for storing and expressing genetic information.

Just four kinds of nucleotides make up all DNA (these are adenine, guanine, cytosine, and thymine), but there can be billions of these molecules lined up in a very specific sequence. Long chains of DNA bind together to form a stable double helix (fig. 3.6). These chains separate and are duplicated when cells divide, so that genetic information is replicated. Every individual has a unique set of DNA molecules, which create the differences between individuals and between species.

Cells are the fundamental units of life

All living organisms are composed of **cells,** minute compartments within which the processes of life are carried out (fig. 3.7). Microscopic organisms such as bacteria, some algae, and protozoa are composed of single cells. Higher organisms have many cells, usually with many different cell varieties. Your body, for instance, is

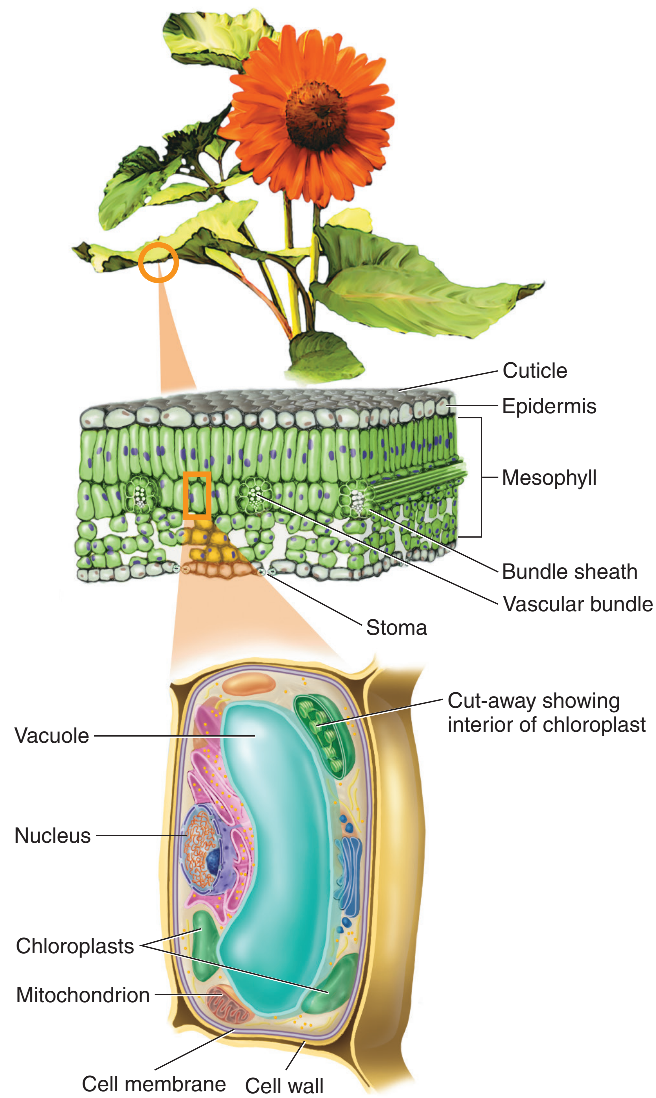

FIGURE 3.7 Plant tissues and a single cell's interior. Cell components include a cellulose cell wall, a nucleus, a large empty vacuole, and several chloroplasts, which carry out photosynthesis.

composed of several trillion cells of about two hundred distinct types. Every cell is surrounded by a thin but dynamic membrane of lipid and protein that receives information about the exterior world and regulates the flow of materials between the cell and its environment. Inside, cells are subdivided into tiny organelles and subcellular particles that provide the machinery for life. Some of these organelles store and release energy. Others manage and distribute information. Still others create the internal structure that gives the cell its shape and allows it to fulfill its role.

A special class of proteins called **enzymes** carry out all the chemical reactions required to create these various structures. Enzymes also provide energy and materials to carry out cell functions, dispose of wastes, and perform other functions of life at the cellular level. Enzymes are molecular catalysts: they regulate chemical reactions without being used up or inactivated in the process. Like hammers or wrenches, they do their jobs without being consumed or damaged as they work. There are generally thousands of different kinds of enzymes in every cell, which carry out the many processes on which life depends. Altogether, the multitude of enzymatic reactions performed by an organism is called its **metabolism.**

Section Review

1. Define and . Are these terms interchangeable?
2. Your body contains vast numbers of carbon atoms. How is it possible that some of these carbon atoms may have been part of the body of a prehistoric creature?
3. What are six characteristics of water that make it so valuable for living organisms and their environment?

3.2 Energy

- *Energy occurs in different forms, such as kinetic energy, potential energy, chemical energy, or heat.*
- *The laws of thermodynamics state that energy is neither created nor destroyed, but that energy degrades to lower-intensity forms when used.*

Energy is the ability to do work, such as moving matter over a distance or causing a heat transfer between two objects at different temperatures. Energy can take many different forms. Heat, light, electricity, and chemical energy are examples that we all experience. Here we examine differences between forms of energy.

Energy varies in intensity

The energy contained in moving objects is called **kinetic energy.** A rock rolling down a hill, the wind blowing through the trees, water flowing over a dam (fig. 3.8), or electrons speeding around the nucleus of an atom are all examples of kinetic energy. **Potential energy** is stored energy that is latent but available for use. A rock poised at the top of a hill and water stored behind a dam are examples of potential energy. **Chemical energy** stored in the food that you eat and the gasoline that you put into your car are also examples of potential energy that can be released

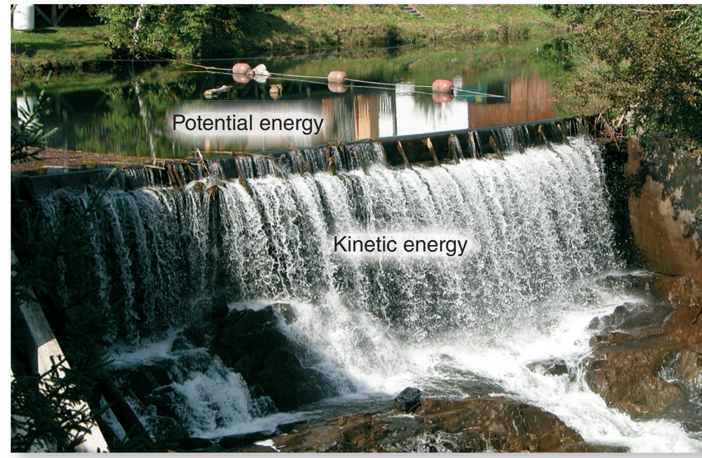

FIGURE 3.8 Water stored behind this dam represents potential energy. Water flowing over the dam has kinetic energy, some of which is converted to heat.

to do useful work. Energy is often measured in units of heat (calories) or work (joules). One joule (J) is the work done when one kilogram is accelerated at one meter per second per second. One calorie is the amount of energy needed to heat one gram of pure water one degree Celsius. A calorie can also be measured as 4.184 J.

Heat is the energy that can be transferred between objects due to their difference in temperature. When a substance absorbs heat, the kinetic energy of its molecules increases, or it may change state: A solid may become a liquid, or a liquid may become a gas. We sense change in heat content as change in temperature (unless the substance changes state).

An object can have a high heat content but a low temperature, such as a lake that freezes slowly in the fall. Other objects, like a burning match, have a high temperature but little heat content. Heat storage in lakes and oceans is essential to moderating climates and maintaining biological communities. Heat absorbed in changing states is also critical. As you will read in chapter 15, evaporation and condensation of water in the atmosphere help distribute heat around the globe.

Energy that is diffused, dispersed, and low in temperature is considered low-quality energy because it is difficult to gather and use for productive purposes. The heat stored in the oceans, for instance, is immense but hard to capture and use, so it is low-quality. Conversely, energy that is intense, concentrated, and high in temperature is high-quality energy because of its usefulness in carrying out work. The intense flames of a very hot fire or high-voltage electrical energy are examples of high-quality forms that are valuable to humans. Many of our alternative energy sources (such as wind) are diffuse compared to the higher-quality, more concentrated chemical energy in oil, coal, or gas.

Thermodynamics regulates energy transfers

Atoms and molecules cycle endlessly through organisms and their environment, but energy flows in a one-way path. A constant supply of energy—nearly all of it from the sun—is needed to keep biological processes running. Energy can be used repeatedly as it flows through the system, and it can be stored temporarily in the chemical bonds of organic molecules, but eventually it is released and dissipated.

The study of thermodynamics deals with how energy is transferred in natural processes. More specifically, it deals with the rates of flow and the transformation of energy from one form or quality to another. Thermodynamics is a complex, quantitative discipline, but you don't need a great deal of math to understand some of the broad principles that shape our world and our lives.

The **first law of thermodynamics** states that energy is *conserved;* that is, it is neither created nor destroyed under normal conditions. Energy may be transformed, for example, from the energy in a chemical bond to heat energy, but the total amount does not change.

The **second law of thermodynamics** states that, with each successive energy transfer or transformation in a system, less energy is available to do work. That is, energy is degraded to lower-quality forms, or it dissipates and is lost, as it is used. When you drive a car, for example, the chemical energy of the gas is degraded to kinetic energy and heat, which dissipates, eventually, to space. The second law recognizes that disorder, or **entropy,** tends to increase in all natural systems. Consequently, there is always less *useful* energy available when you finish a process than there was before you started. Because of this loss, everything in the universe tends to fall apart, slow down, and get more disorganized.

How does the second law of thermodynamics apply to organisms and biological systems? Organisms are highly organized, both structurally and metabolically. Constant care and maintenance is required to keep up this organization, and a constant supply of energy is required to maintain these processes. Every time some energy is used by a cell to do work, some of that energy is dissipated or lost as heat. If cellular energy supplies are interrupted or depleted, the result—sooner or later—is death.

Section Review

1. Restate the first and second law of thermodynamics.
2. The oceans store a vast amount of heat, but why (except for climate moderation) is this huge reservoir of energy of little use to humans?
3. Explain the difference between high-quality and low-quality energy.

3.3 Energy for Life

- *Nearly all energy for life comes from the sun.*
- *Green plants capture this energy through photosynthesis; plants and animals release this energy through cellular respiration.*

The sun provides energy for nearly all plants and animals on earth. In this section we examine how organisms capture and use this energy. We also explore an alternative energy source, chemical reactions using elements from the earth's crust.

Extremophiles gain energy without sunlight

Until recently, the deep ocean floor was believed to be essentially lifeless. Cold, dark, subject to crushing pressures, and without any known energy supply, it was a place where scientists thought nothing could survive. Undersea explorations in the 1970s, however, revealed dense colonies of animals—blind shrimp, giant tubeworms, strange crabs, and bizarre clams—clustered around vents called black chimneys, where boiling hot, mineral-laden water bubbles up through cracks in the earth's crust. How do these sunless ecosystems get energy? The answer is **chemosynthesis,** the process in which bacteria use chemical bonds between inorganic elements, such as hydrogen sulfide (H_2S) or hydrogen gas (H_2), to provide energy for synthesis of organic molecules.

Discovering organisms living under the severe conditions of deep-sea hydrothermal vents led to exploration of other sites that seem exceptionally harsh to us. Fascinating organisms have been discovered in hot springs, such as in Yellowstone National Park, in intensely salty lakes, and even in deep rock formations, up to 1,500 m (nearly a mile) deep in Columbia River basalts. Some species are amazingly hardy. The recently described *Pyrolobus fumarii* can withstand temperatures up to 113°C (235°F). Most of these extremophiles are archaea, single-celled organisms that are thought to be the most primitive of all living organisms, and the conditions under which they live are thought to be similar to those in which life first evolved.

Deep-sea exploration of areas without thermal vents also has found abundant life (fig. 3.9). We now know that archaea live in oceanic sediments in astonishing numbers. The deepest of these species (they can be 800 m or more below the ocean floor) make methane from gaseous hydrogen (H_2) and carbon dioxide (CO_2), derived from rocks. Other species oxidize methane using sulfur to create hydrogen sulfide (H_2S), which is consumed by bacteria, which serve as a food source for more complex organisms such as tubeworms, crabs, and shrimp.

The vast supply of methane generated by this community could be either a great resource or a terrible threat to us. The total amount of methane made by these microbes is probably greater than all the known reserves of coal, gas, and oil. If we could safely

FIGURE 3.9 A colony of tube worms and mussels cluster over a cool, deep-sea methane seep in the Gulf of Mexico.

extract the huge supplies of methane hydrate in ocean sediments, it could supply our energy needs for hundreds of years. Of greater immediate importance is that if methane-eating microbes weren't intercepting the methane produced by their neighbors, more than 300 million tons per year of this potent greenhouse gas would probably be bubbling to the surface, and we'd have runaway global warming. Methane-using bacteria can also help clean up pollution. After the Deepwater Horizon oil spill in the Gulf of Mexico in 2010, a deep-sea bloom of methane-metabolizing bacteria apparently consumed most of the methane (natural gas) escaping the spill.

Green plants get energy from the sun. Our sun is a star, a fiery ball of exploding hydrogen gas. Its energy comes from fission of hydrogen atoms, which releases intense ultraviolet energy and nuclear radiation (fig. 3.10), yet life here depends upon this searing energy source.

Solar energy is essential to life for two main reasons. First, the sun provides warmth. Most organisms survive within a relatively narrow temperature range: above 40°C, most biomolecules begin to break down or become distorted and nonfunctional. At low temperatures (near 0°C), some chemical reactions of metabolism occur too slowly to enable organisms to grow and reproduce. Other planets in our solar system are either too hot or too cold to support life as we know it. The earth's water and atmosphere help to moderate, maintain, and distribute the sun's heat.

Second, nearly all organisms on the earth's surface depend on solar radiation for life-sustaining energy, which is captured by green plants, algae, and some bacteria in a process called **photosynthesis.** Photosynthesis converts radiant energy into high-quality chemical energy in the bonds that hold together organic molecules. Photosynthetic organisms (plants, algae, and bacteria) capture roughly 105 billion metric tons of carbon every year and store it as biomass. About half of this carbon capture is on land; about half is in the ocean.

This photosynthesis is accomplished using particular wavelengths of solar radiation that pass through our earth's atmosphere and reach the surface. About 45 percent of the radiation at the surface is visible, another 45 percent is infrared, and 10 percent is ultraviolet. Photosynthesis uses mostly the most abundant wavelengths, visible and near infrared. Of the visible wavelengths, photosynthesis uses mainly red and blue light. Most plants reflect green wavelengths, so that is the color they appear to us. Half of the energy plants absorb is used in evaporating water. In the end, only 1 to 2 percent of the sunlight falling on plants is available for photosynthesis. This small percentage is the energy base for virtually all life in the biosphere.

Photosynthesis captures energy; respiration releases that energy

Photosynthesis occurs in tiny organelles called chloroplasts that reside within plant cells (see fig. 3.7). The main key to this process is chlorophyll, a green molecule that can absorb light energy and use the energy to create high-energy chemical in compounds that serve as the fuel for all subsequent cellular metabolism. Chlorophyll doesn't do this important job all alone, however. It is assisted by a large group of other lipid, sugar, protein, and nucleotide molecules. Together these components carry out two interconnected cyclic sets of reactions (fig. 3.11).

Photosynthesis begins with a series of *light-dependent reactions*. These use solar energy directly to split water molecules into oxygen (O_2), which is released to the atmosphere, and hydrogen (H). This is the source of all the oxygen in the atmosphere on which all animals, including you, depend for life. Separating the hydrogen atom from its electron produces H^+ and an electron, both of which are used to form mobile, high-energy molecules called adenosine triphosphate (ATP) and nicotinamide adenine dinucleotide phosphate (NADPH).

Light-independent reactions then use the energy stored in ATP and NADPH molecules to create simple carbohydrates and sugar molecules (glucose, $C_6H_{12}O_6$) from carbon atoms (from CO_2) and water (H_2O). Glucose provides the energy and the building blocks for larger, more complex organic molecules. As ATP and NADPH give up some of their chemical energy, they are transformed to

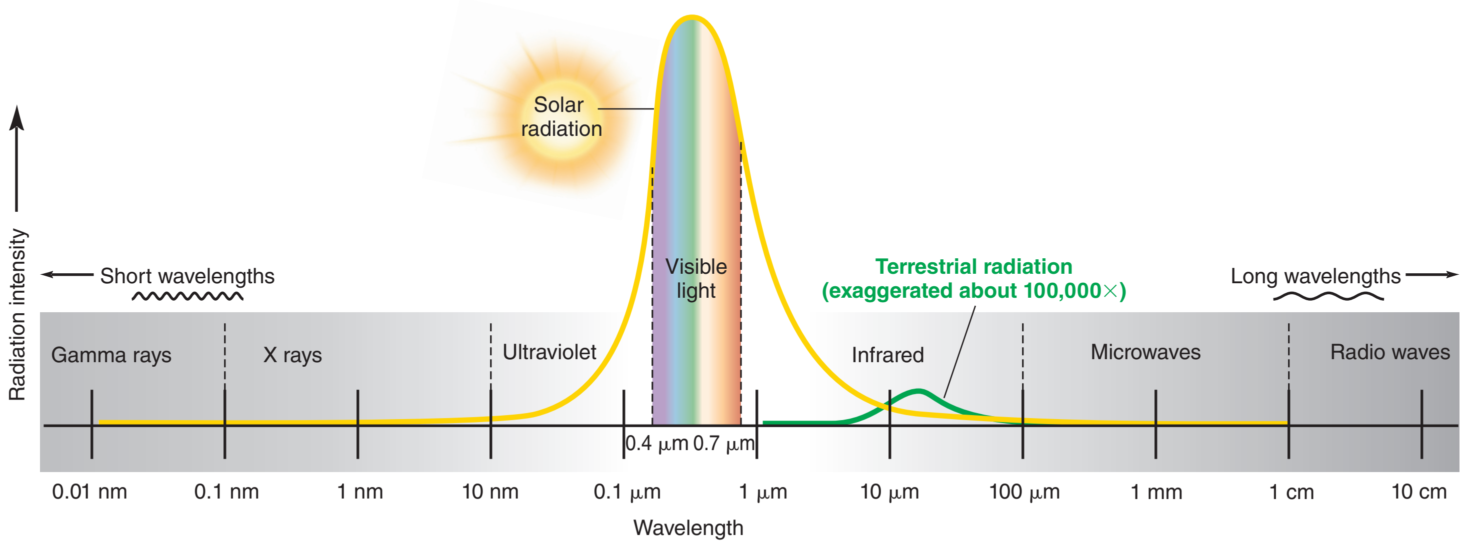

FIGURE 3.10 The electromagnetic spectrum. Our eyes are sensitive to light wavelengths, which make up nearly half the energy that reaches the earth's surface (represented by the area under the curve). Photosynthesizing plants also use the most abundant solar wavelengths. The earth reemits lower-energy, longer wavelengths, mainly the infrared part of the spectrum.