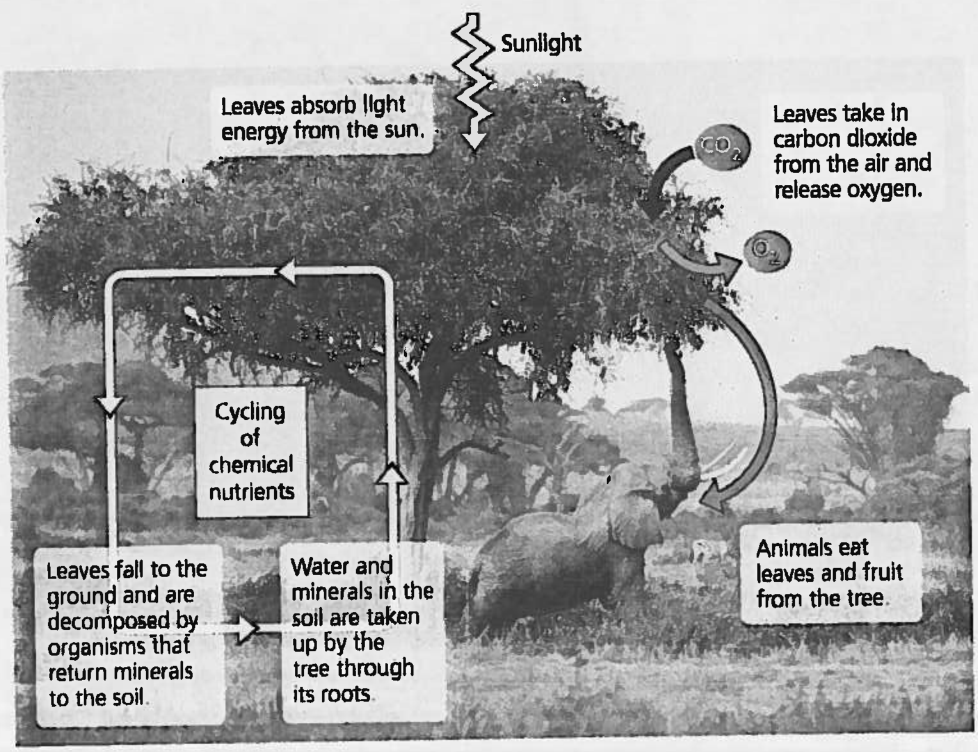
Systems biology is relevant to the study of life at all levels. During the early years of the 20th century, biologists studying how animal bodies function (animal physiology) began integrating data on how multiple organs coordinate processes such as the regulation of sugar concentration in the blood. And in the 1960s, scientists investigating ecosystems pioneered a more mathematically sophisticated systems approach with elaborate models diagramming the network of interactions between organisms and nonliving components of ecosystems, such as salt marshes. More recently, with the sequencing of DNA from many species, systems biology has taken hold at the cellular and molecular levels, as we'll describe later when we discuss DNA.

Theme: Organisms Interact with Other Organisms and the Physical Environment

Turn back again to Figure 1.4, this time focusing on the forest. In an ecosystem, each organism interacts continuously with its environment, which includes both other organisms and physical factors. The leaves of a tree, for example, absorb light from the sun, take in carbon dioxide from the air, and release oxygen to the air (**Figure 1.5**). Both the organism and the environment are affected by the interactions between them. For example, a plant takes up water and minerals from the soil through its roots, and its roots help form soil by breaking up rocks. On a global scale, plants and other photosynthetic organisms have generated all the oxygen in the air.



▲ **Figure 1.5 Interactions of an African acacia tree with other organisms and the physical environment.**

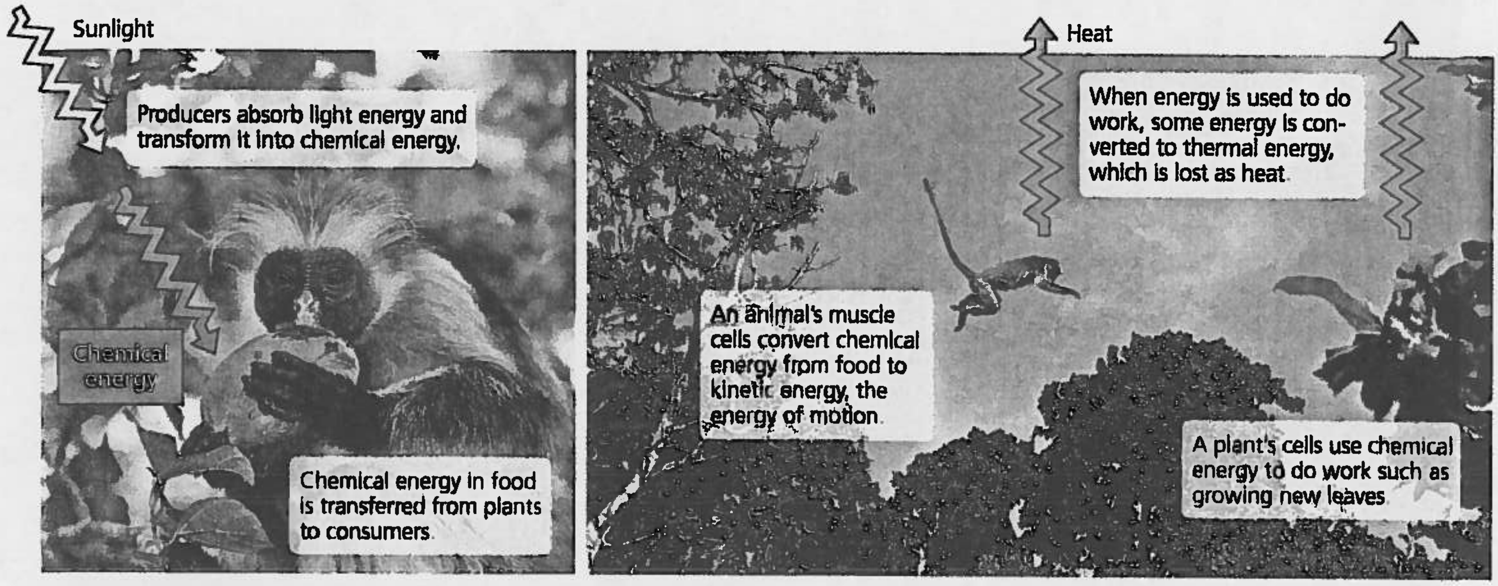
A tree also interacts with other organisms, such as soil microorganisms associated with its roots, insects that live in the tree, and animals that eat its leaves and fruit. Interactions between organisms ultimately result in the cycling of nutrients in ecosystems. For example, minerals acquired by a tree will eventually be returned to the soil by other organisms that decompose leaf litter, dead roots, and other organic debris. The minerals are then available to be taken up by plants again.

Like all organisms, we humans interact with our environment. Unfortunately, our interactions sometimes have drastic consequences. For example, since the Industrial Revolution in the 1800s, the burning of fossil fuels (coal, oil, and gas) has been increasing at an ever-accelerating pace. This practice releases gaseous compounds into the atmosphere, including prodigious amounts of carbon dioxide (CO_2). About half the human-generated CO_2 stays in the atmosphere, acting like a layer of glass around the planet that admits radiation that warms the Earth but prevents heat from radiating into outer space. Scientists estimate that the average temperature of the planet has risen 1°C since 1900 due to this "greenhouse effect," and they project an additional rise in average global temperature of at least 3°C over the course of the 21st century.

This global warming, a major aspect of **global climate change**, has already had dire effects on life-forms and their habitats all over planet Earth. Polar bears have lost a significant portion of the ice platform from which they hunt, and there are examples of small rodents and plant species that have shifted their ranges to higher altitudes, as well as bird populations that have altered their migration schedules. Only time will reveal the consequences of these changes. Scientists predict that even if we stopped burning fossil fuels today, it would take several centuries to return to preindustrial CO_2 levels. That scenario is highly improbable, so it is imperative that we learn all we can about the effects of global climate change on Earth and its populations. Acting as the stewards of our planet, we must strive to find ways to address this problem.

Theme: Life Requires Energy Transfer and Transformation

As you saw in Figure 1.5, a tree's leaves absorb sunlight. The input of energy from the sun makes life possible: A fundamental characteristic of living organisms is their use of energy to carry out life's activities. Moving, growing, reproducing, and the other activities of life are work, and work requires energy. In the business of living, organisms often



(a) Energy flow from sunlight to producers to consumers

(b) Using energy to do work

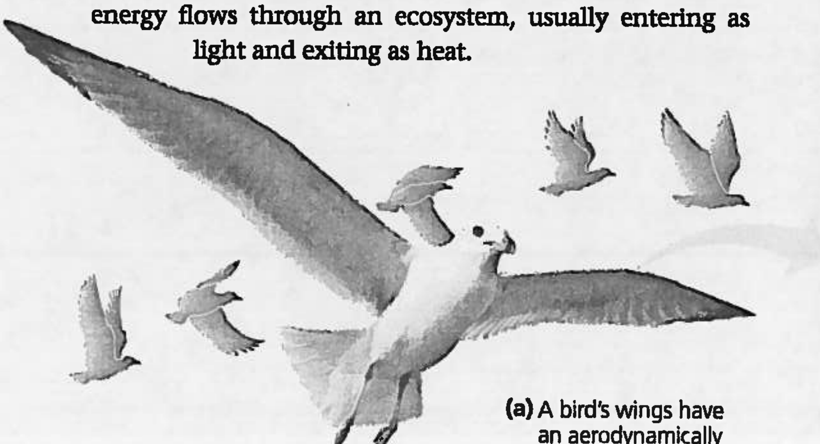
▲ **Figure 1.6 Energy flow in an ecosystem.** This endangered Red Colobus monkey lives in Tanzania.

transform one form of energy to another. Chlorophyll molecules within the tree's leaves harness the energy of sunlight and use it to drive photosynthesis, converting carbon dioxide and water to sugar and oxygen. The chemical energy in sugar is then passed along by plants and other photosynthetic organisms (producers) to consumers. Consumers are organisms, such as animals, that feed on producers and other consumers **(Figure 1.6a)**.

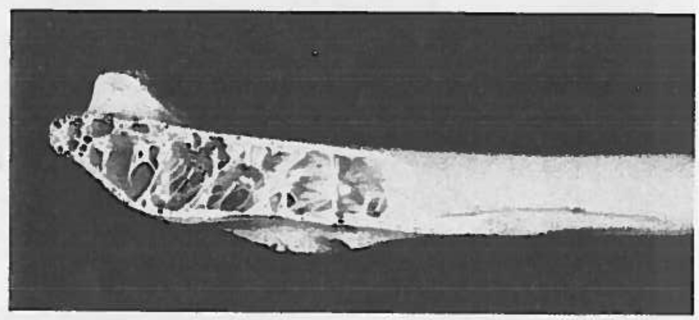
An animal's muscle cells use sugar as fuel to power movements, converting chemical energy to kinetic energy, the energy of motion **(Figure 1.6b)**. The cells in a leaf use sugar to drive the process of cell proliferation during leaf growth, transforming stored chemical energy into cellular work. In both cases, some of the energy is converted to thermal energy, which dissipates to the surroundings as heat. In contrast to chemical nutrients, which recycle within an ecosystem, energy flows through an ecosystem, usually entering as light and exiting as heat.

Theme: Structure and Function Are Correlated at All Levels of Biological Organization

Another theme evident in Figure 1.4 is the idea that form fits function, which you'll recognize from everyday life. For example, a screwdriver is suited to tighten or loosen screws, a hammer to pound nails. How a device works is correlated with its structure. Applied to biology, this theme is a guide to the anatomy of life at all its structural levels. An example from Figure 1.4 is seen in the leaf: Its thin, flat shape maximizes the amount of sunlight that can be captured by its chloroplasts. Analyzing a biological structure gives us clues about what it does and how it works. Conversely, knowing the function of something provides insight into its construction. An example from the animal kingdom, the wing of a bird, provides additional instances of the structure-function theme **(Figure 1.7)**. In exploring life on its different structural levels, we discover functional beauty at every turn.



(a) A bird's wings have an aerodynamically efficient shape.



(b) Wing bones have a honeycombed internal structure that is strong but lightweight.

▲ **Figure 1.7 Form fits function in a gull's wing. (a)** The shape of a bird's wings and **(b)** the structure of its bones make flight possible.

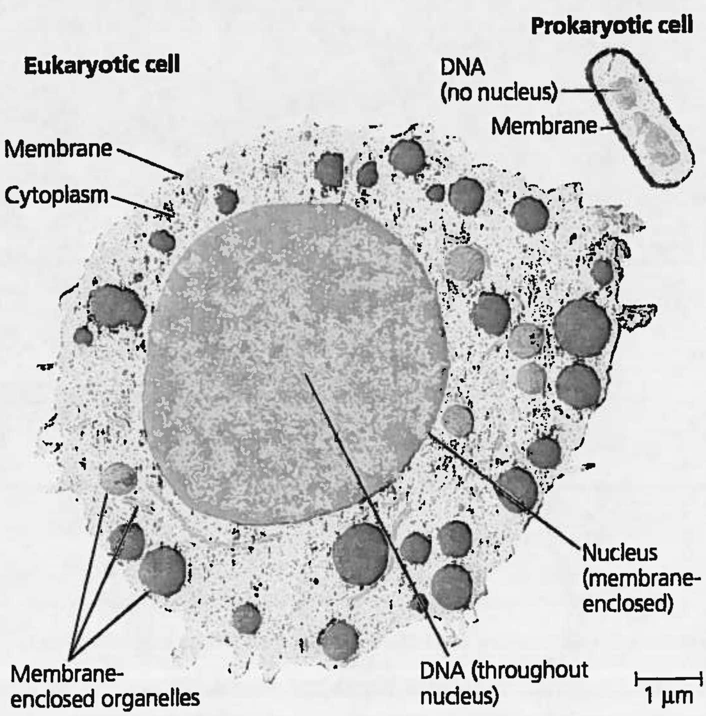
? *How does form fit function in a human hand?*

Theme: The Cell Is an Organism's Basic Unit of Structure and Function

In life's structural hierarchy, the cell has a special place as the lowest level of organization that can perform all activities required for life. Moreover, the activities of organisms are all based on the activities of cells. For instance, the movement of your eyes as you read this line is based on activities of muscle and nerve cells. Even a global process such as the recycling of carbon is the cumulative product of cellular activities, including the photosynthesis that occurs in the chloroplasts of leaf cells. Understanding how cells work is a major focus of biological research.

All cells share certain characteristics. For example, every cell is enclosed by a membrane that regulates the passage of materials between the cell and its surroundings. And every cell uses DNA as its genetic information. However, we can distinguish between two main forms of cells: prokaryotic cells and eukaryotic cells. The cells of two groups of microorganisms, called bacteria (singular, *bacterium*) and archaea (singular, *archaean*), are prokaryotic. All other forms of life, including plants and animals, are composed of eukaryotic cells.

A **eukaryotic cell** is subdivided by internal membranes into various membrane-enclosed organelles (**Figure 1.8**). In most eukaryotic cells, the largest organelle is the nucleus, which contains the cell's DNA. The other organelles are located in the cytoplasm, the entire region between the nucleus and outer membrane of the cell. The chloroplast you saw in Figure 1.4 is an organelle found in eukaryotic cells that carry out photosynthesis. Prokaryotic cells are much simpler and generally smaller than eukaryotic cells, as seen clearly in Figure 1.8. In a **prokaryotic cell**, the DNA is not separated from the rest of the cell by enclosure in a membrane-bounded nucleus. Prokaryotic cells also lack the other kinds of membrane-enclosed organelles that characterize eukaryotic cells. The properties of all organisms, whether prokaryotic or eukaryotic, are based in the structure and function of cells.



▲ **Figure 1.8 Contrasting eukaryotic and prokaryotic cells in size and complexity.**

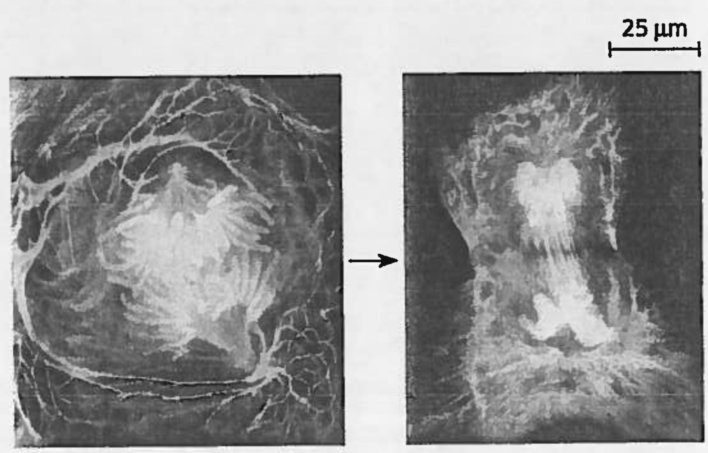
Theme: The Continuity of Life Is Based on Heritable Information in the Form of DNA

The division of cells to form new cells is the foundation for all reproduction and for the growth and repair of multicellular organisms. Inside the dividing cell in **Figure 1.9**, you can see structures called chromosomes, which are stained with a blue-glowing dye. The chromosomes have almost all of the cell's genetic material, its **DNA** (short for deoxyribonucleic acid). DNA is the substance of **genes**, the units of inheritance that transmit information from parents to offspring. Your blood group (A, B, AB, or O), for example, is the result of certain genes that you inherited from your parents.

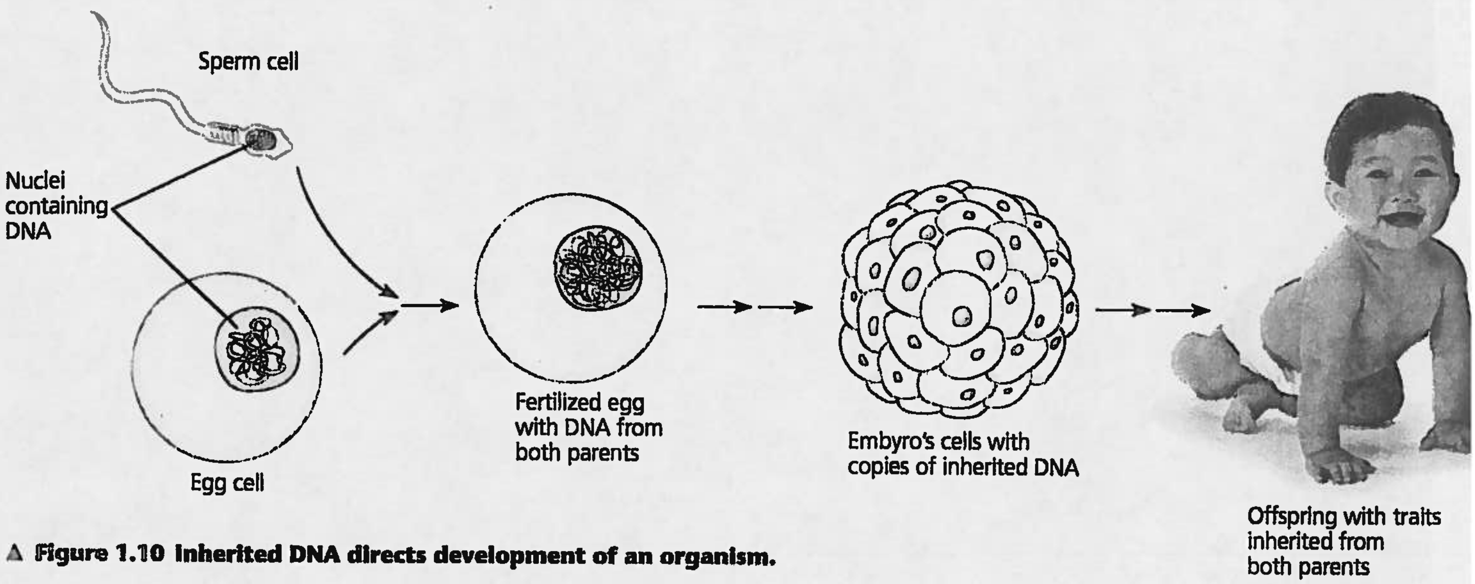
DNA Structure and Function

Each chromosome contains one very long DNA molecule, with hundreds or thousands of genes arranged along its length. The genes encode the information necessary to build other molecules in the cell, most notably proteins. Proteins play structural roles and are also responsible for carrying out cellular work. They thus establish a cell's identity.

The DNA of chromosomes replicates as a cell prepares to divide, and each of the two cellular offspring inherits a complete set of genes, identical to that of the parent cell. Each of us began life as a single cell stocked with DNA inherited from our parents. Replication of that DNA with each round of cell division transmitted copies of the DNA to our trillions of cells. The DNA controls the development and maintenance of the entire organism and, indirectly, everything the organism does (**Figure 1.10**). The DNA serves as a central database.



▲ **Figure 1.9 A lung cell from a newt divides into two smaller cells that will grow and divide again.**

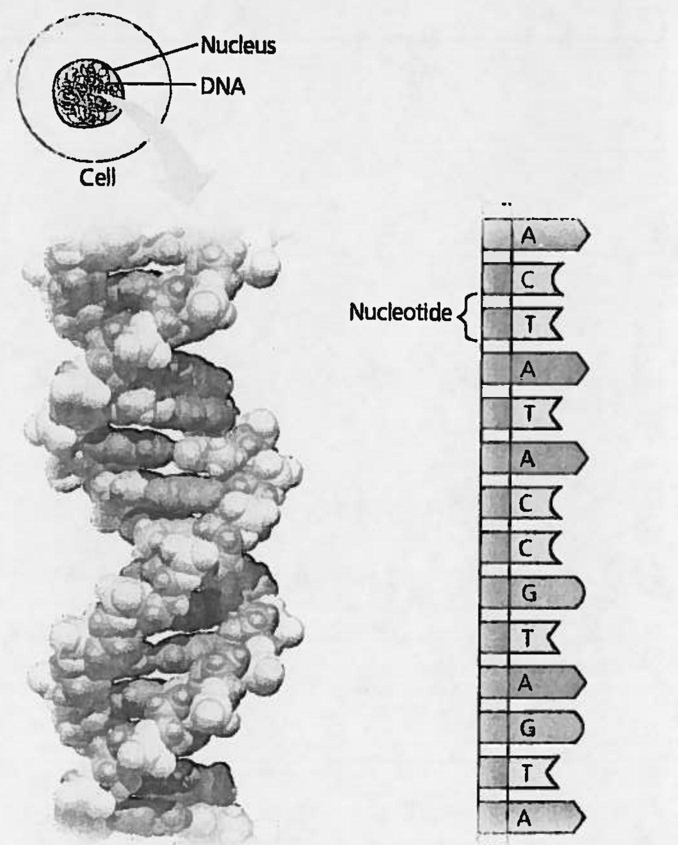


▲ **Figure 1.10 Inherited DNA directs development of an organism.**

The molecular structure of DNA accounts for its ability to store information. Each DNA molecule is made up of two long chains, called strands, arranged in a double helix. Each chain is made up of four kinds of chemical building blocks called nucleotides, abbreviated A, T, C, and G (**Figure 1.11**). The way DNA encodes information is analogous to how we arrange the letters of the alphabet into precise sequences with specific meanings. The word *rat,* for example, evokes a rodent; the words *tar* and *art,* which contain the same letters, mean very different things. We can think of nucleotides as a four-letter alphabet of inheritance. Specific sequential arrangements of these four nucleotide letters encode the information in genes, which are typically hundreds or thousands of nucleotides long.

DNA provides the blueprints for making proteins, and proteins are the main players in building and maintaining the cell and carrying out its activities. For instance, the information carried in a bacterial gene may specify a certain protein in a bacterial cell membrane, while the information in a human gene may denote a protein hormone that stimulates growth. Other human proteins include proteins in a muscle cell that drive contraction and the defensive proteins called antibodies. Enzymes, which catalyze (speed up) specific chemical reactions, are mostly proteins and are crucial to all cells.

The DNA of genes controls protein production indirectly, using a related kind of molecule called RNA as an intermediary. The sequence of nucleotides along a gene is transcribed into RNA, which is then translated into a specific protein with a unique shape and function. This entire process, by which the information in a gene directs the production of a cellular product, is called **gene expression.** In translating genes into proteins, all forms of life employ essentially the same genetic code. A particular sequence of nucleotides says the same thing in one organism as it does in another. Differences between organisms reflect differences between their nucleotide sequences rather than between their genetic codes.



(a) DNA double helix. This model shows each atom in a segment of DNA. Made up of two long chains of building blocks called nucleotides, a DNA molecule takes the three-dimensional form of a double helix.

(b) Single strand of DNA. These geometric shapes and letters are simple symbols for the nucleotides in a small section of one chain of a DNA molecule. Genetic information is encoded in specific sequences of the four types of nucleotides. (Their names are abbreviated A, T, C, and G.)

▲ **Figure 1.11 DNA: The genetic material.**

Not all RNA molecules in the cell are translated into protein; some RNAs carry out other important tasks. We have known for decades that some types of RNA are actually components of the cellular machinery that manufactures proteins. Recently, scientists have discovered whole new classes of RNA that play other roles in the cell, such as regulating the functioning of protein-coding genes. All these RNAs are specified by genes, and the process of their transcription is also referred to as gene expression. By carrying the instructions for making proteins and RNAs and by replicating with each cell division, DNA ensures faithful inheritance of genetic information from generation to generation.

Genomics: Large-Scale Analysis of DNA Sequences

The entire "library" of genetic instructions that an organism inherits is called its **genome**. A typical human cell has two similar sets of chromosomes, and each set has DNA totaling about 3 billion nucleotide pairs. If the one-letter abbreviations for the nucleotides of one strand were written in letters the size of those you are now reading, the genetic text would fill about 600 books the size of this one. Within this genomic library of nucleotide sequences are genes for about 75,000 kinds of proteins and an as yet unknown number of RNA molecules that do not code for proteins.

Since the early 1990s, the pace at which we can sequence genomes has accelerated at an almost unbelievable rate, enabled by a revolution in technology. The development of new methods and DNA-sequencing machines, such as those shown in **Figure 1.12**, have led the charge. The entire sequence of nucleotides in the human genome is now known, along with the genome sequences of many other organisms, including bacteria, archaea, fungi, plants, and other animals.

The sequencing of the human genome was heralded as a scientific and technological achievement comparable to landing the *Apollo* astronauts on the moon in 1969. But it was only the beginning of an even bigger research endeavor, an effort to learn how the activities of the myriad proteins encoded by the DNA are coordinated in cells and whole organisms. To make sense of the deluge of data from genome-sequencing projects and the growing catalog of known protein functions, scientists are applying a systems approach at the cellular and molecular levels. Rather than investigating a single gene at a time, these researchers have shifted to studying whole sets of genes of a species as well as comparing genomes between species—an approach called **genomics**.

▲ **Figure 1.12 Biology as an information science.** Automatic DNA-sequencing machines and abundant computing power make the sequencing of genomes possible. This facility in Walnut Creek, California, is part of the Joint Genome Institute.

Three important research developments have made the genomic approach possible. One is "high-throughput" technology, tools that can analyze biological materials very rapidly and produce enormous amounts of data. The automatic DNA-sequencing machines that made the sequencing of the human genome possible are examples of high-throughput devices (see Figure 1.12). The second major development is **bioinformatics**, the use of computational tools to store, organize, and analyze the huge volume of data that result from high-throughput methods. The third key development is the formation of interdisciplinary research teams—melting pots of diverse specialists that may include computer scientists, mathematicians, engineers, chemists, physicists, and, of course, biologists from a variety of fields.

Theme: Feedback Mechanisms Regulate Biological Systems

Just as a coordinated control of traffic flow is necessary for a city to function smoothly, regulation of biological processes is crucial to the operation of living systems. Consider your muscles, for instance. When your muscle cells require more energy during exercise, they increase their consumption of the sugar molecules that serve as fuel. In contrast, when you rest, a different set of chemical reactions converts surplus sugar to storage molecules.

Like most of the cell's chemical processes, those that either decompose or store sugar are accelerated, or catalyzed, by proteins called enzymes. Each type of enzyme catalyzes a specific chemical reaction. In many cases, these reactions are linked into chemical pathways, each step with its own enzyme. How does the cell coordinate its various chemical pathways? In our example of sugar management, how does the cell match fuel supply to demand, regulating its opposing pathways of sugar consumption and storage? The key is the ability of many biological processes to self-regulate by a mechanism called feedback.

In feedback regulation, the output, or product, of a process regulates that very process. The most common form of regulation in living systems is **negative feedback**, in which accumulation of an end product of a process slows that process. For example, the cell's breakdown of sugar generates chemical energy in the form of a substance called ATP. When a cell makes more ATP than it can use, the excess ATP "feeds back"