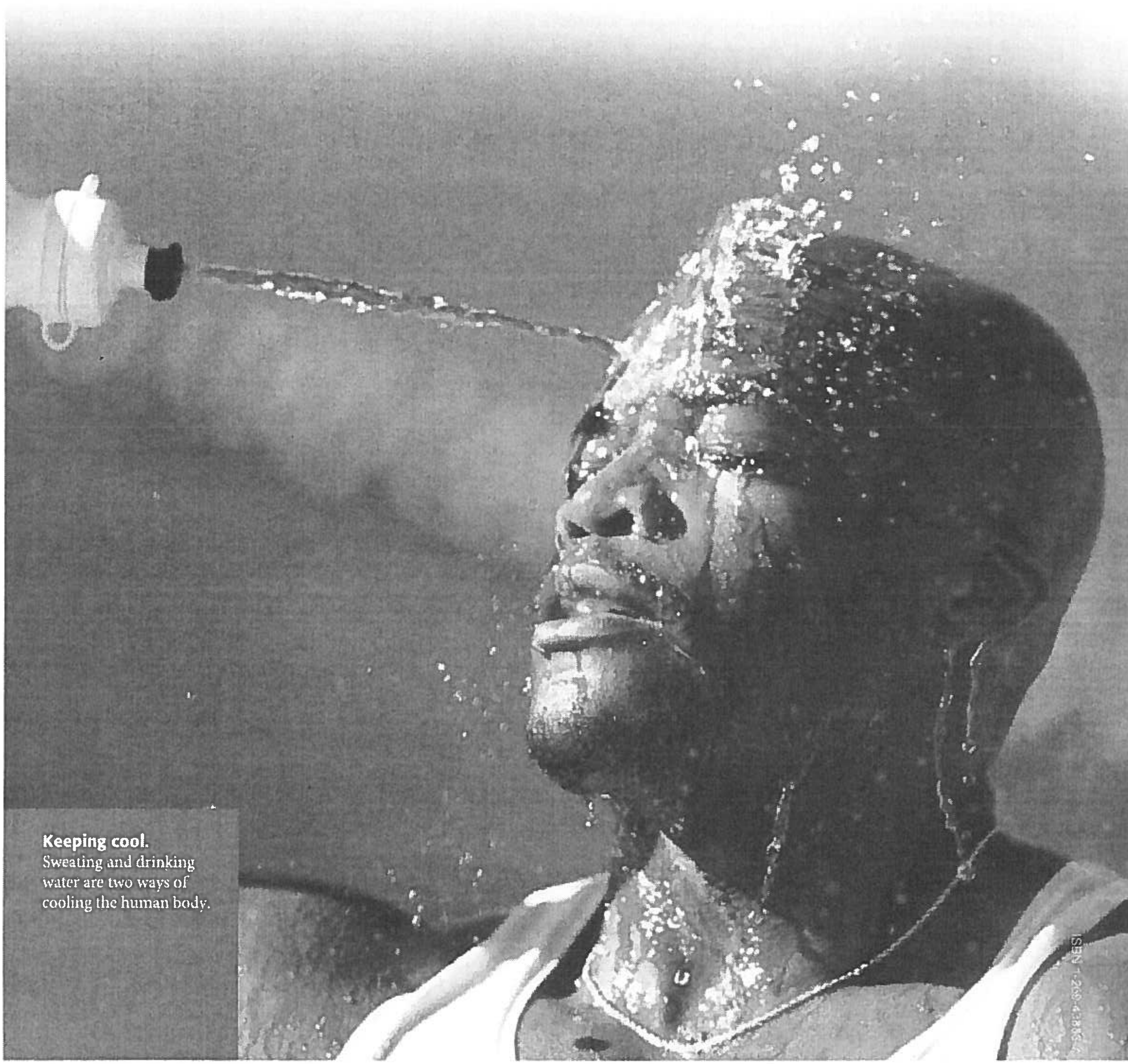
21 Unifying Concepts of Animal Structure and Function



Keeping cool.
Sweating and drinking water are two ways of cooling the human body.

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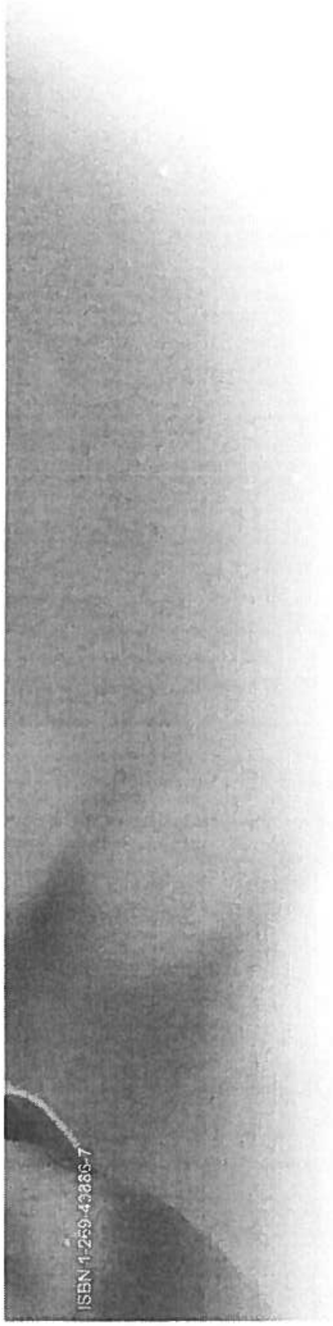
CHAPTER THREAD

Controlling Body Temperature



Controlling Body Temperature BIOLOGY AND SOCIETY

An Avoidable Tragedy

August 20, 2008, started off as a normal day for the football team at Pleasure Ridge Park High School. True, the day was sweltering, with a heat index of 94, but such conditions are common during Kentucky summers. However, this day turned tragic when Max Gilpin, a healthy 15-year-old sophomore offensive lineman, began to have trouble breathing during the team's routine training and collapsed. By the time he reached the hospital, his body temperature was 107 degrees Fahrenheit. Max died three days later from heat stroke. As heartbreaking as it is, this case is hardly unique: Heat illness is a leading cause of death and injury among U.S. high school athletes, affecting nearly 10,000 each year.

When you play or work hard, your muscles produce a lot of heat. In response, a temperature control center in your brain initiates responses that help keep your internal temperature near its normal value (about 37°C, or 99°F). Sweating cools your skin by evaporation and blood vessels near the skin surface expand, allowing more heat to be released. But what if the heat worsens? Surface blood vessels widen to their maximum, and excessive sweating may cause dehydration. Both of these responses could lower blood pressure enough to cause you to faint. This set of symptoms, called heat exhaustion, represents the body's final attempt to cool itself. To avoid heat exhaustion, you should drink plenty of water and rest if you feel lightheaded or your skin flushes excessively.

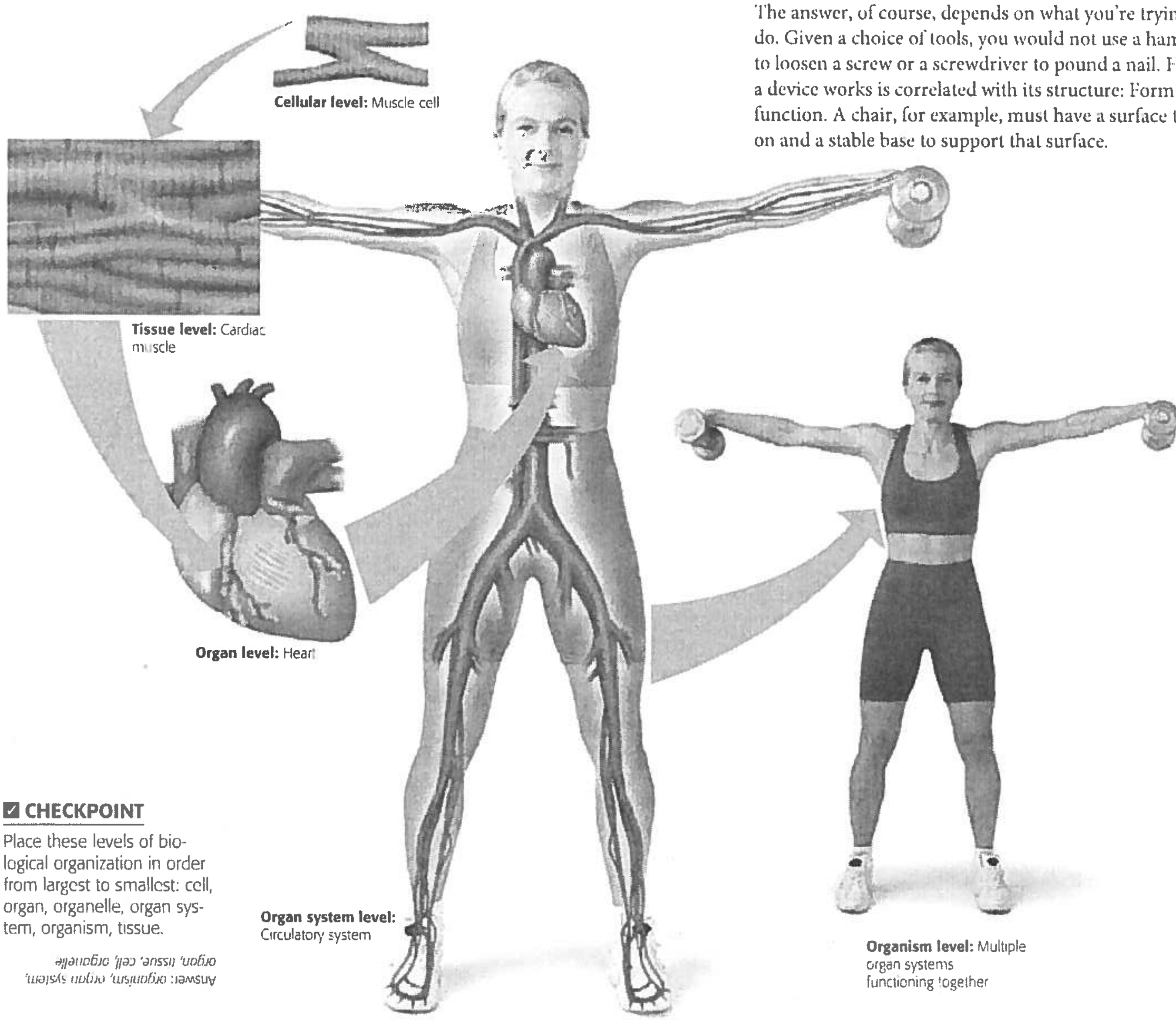
Under extreme conditions, a severely elevated body temperature can disrupt the brain's control center. When the body loses its ability to self-regulate, sweating stops and the skin becomes hot and dry. The body's organs begin to fail as a result of the extreme heat, and brain damage and death can quickly follow unless the body is rapidly cooled and provided with fluids. This condition, called heat stroke, is caused by a total breakdown of the body's internal temperature control system.

In this unit, you will learn how your body works, including its self-regulating mechanisms. We'll concentrate on humans but offer comparisons to other animals to provide examples of different solutions to a common set of problems. How, for example, do creatures as diverse as hydras, halibut, and humans regulate body temperature or obtain food? By learning about various evolutionary adaptations common to animals, you will better understand your own body. To set the stage for the rest of the unit, this chapter begins with a description of basic animal structure, from cells to tissues to organs to organ systems. Next, these structural principles will be applied to two examples of how animals regulate their internal environment: the control of temperature and the control of water and solute movement.

The Structural Organization of Animals

Life is characterized by a hierarchy of organization. In animals, individual cells are grouped into tissues, which in turn are grouped into organs, which participate in organ systems, which together make up the entire organism (**Figure 21.1**). Parts of the body at each level of the hierarchy act together to perform the functions of life, such as regulating an animal's internal environment. For example, regulation of your body temperature requires the cooperation of several levels of body organization. The brain, an organ, sends signals via the nervous system that trigger specific changes in tissues (such as the narrowing or widening of capillaries near the skin) and individual cells (such as an increase or decrease in glucose metabolism). The result is a change within the whole body. ☑

▼**Figure 21.1 Structural hierarchy in a human.**



Form Fits Function

Which is the better tool: a hammer or a screwdriver? The answer, of course, depends on what you're trying to do. Given a choice of tools, you would not use a hammer to loosen a screw or a screwdriver to pound a nail. How a device works is correlated with its structure: Form fits function. A chair, for example, must have a surface to sit on and a stable base to support that surface.

☑ CHECKPOINT

Place these levels of biological organization in order from largest to smallest: cell, organ, organelle, organ system, organism, tissue.

Answer: organism, organ system, organ, tissue, cell, organelle

These structural elements are dictated by the task that the chair must perform. The same principle applies to life at its many structural levels, from cells to organisms. Analyzing a biological structure gives us clues about what it does and how it works. Conversely, knowing the function of a structure provides insight about its construction. In exploring life at its many levels, we will discover functional elegance at every turn (**Figure 21.2**).

When discussing structure and function, biologists distinguish anatomy from physiology. **Anatomy** is the study of the structure of an organism's parts. **Physiology** is the study of the function of those parts. For example, an anatomist might study the arrangement of blood vessels near the surface of the skin, whereas a physiologist might study how those blood vessels widen in response to a sudden rise in temperature. Despite their different approaches, the two disciplines serve the same purpose: to better understand the connections between structure and function.

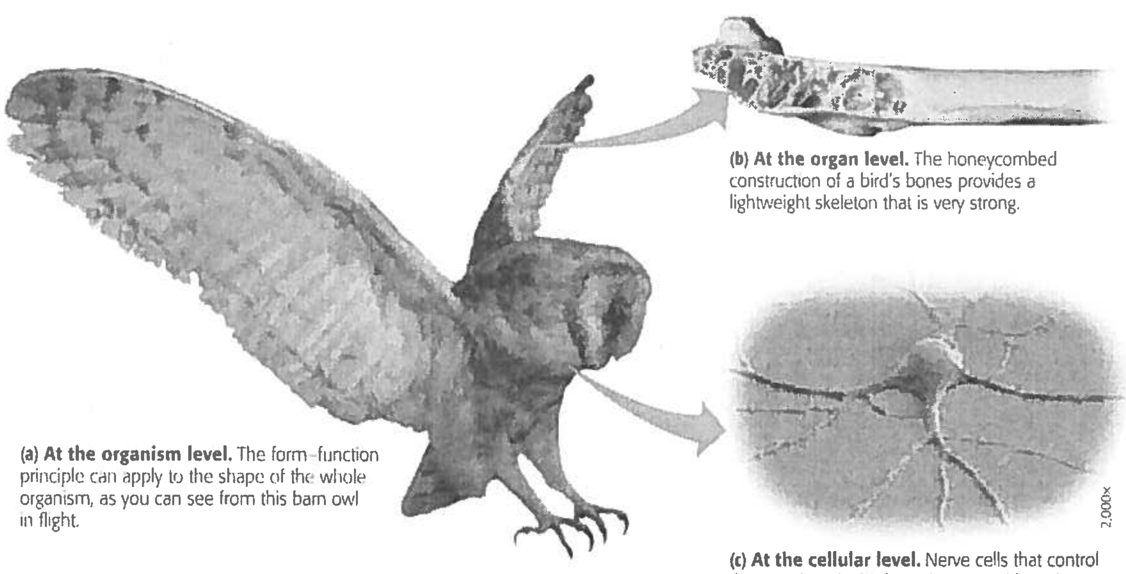
The correlation of form (structure) and function is a fundamental principle of biology that is evident at all levels of life's hierarchy; it is a principle that will guide us throughout our study of animals. But this rule of "design" does not mean that such biological tools as a bird's wings, a fish's gills, or a mammal's blood vessels are products of purposeful invention. Here the analogy to household tools such as hammers and screwdrivers fails because those tools were designed with specific goals. It is natural selection that refines biological equipment to the current environment. It does so by screening for the most effective variations among individuals of a population—those variations that are most advantageous in the local environment. Generations of selecting for what works best in a particular environment will fit form to function without any goal-oriented plan. Thus, the form–function principle is just another facet of biology's unifying theme: evolution. ☑

Tissues

The cell is the basic unit of all living organisms. In almost all animals, including humans, cells rarely act alone but instead are grouped into tissues. A **tissue** is an integrated group of similar cells that performs a specific function. The cells composing a tissue are specialized; they have an overall structure that enables them to perform a specific task.

Some tissues consist of living cells surrounded by a meshwork of nonliving fibers. The cells of other tissues are held together by a sticky substance that coats the cells or by special junctions that fuse the cells together. An animal has four main categories of tissue: epithelial tissue, connective tissue, muscle tissue, and nervous tissue. As you'll see, the structure of each type of tissue relates to its specific function.

▼Figure 21.2 **Form fits function.**



(a) At the organism level. The form–function principle can apply to the shape of the whole organism, as you can see from this barn owl in flight.

(b) At the organ level. The honeycombed construction of a bird's bones provides a lightweight skeleton that is very strong.

(c) At the cellular level. Nerve cells that control the muscles of a bird or other animal have long extensions that transmit signals.

☑ CHECKPOINT

1. What is the difference between anatomy and physiology?
2. Explain how a tennis racket illustrates the "form fits function" principle.

*Answers: **1.** Anatomy is the study of structure, whereas physiology is the study of function. **2.** To aid the function of hitting a ball, a tennis racket has a handle for gripping, a large head to strike the ball, and strings to provide bounce.*

Epithelial Tissue

The tissue that covers the surface of the body and lines organs is called **epithelial tissue**, also known as **epithelium** **(Figure 21.3)**. The epidermis (outer layer of skin) and the linings of the heart, blood vessels, and digestive tract are examples. Epithelial tissue is made of sheets of tightly packed cells that are fused together. The architecture of an epithelium illustrates how structure fits function at the tissue level. For example, your epidermis contains dense layers of tightly bound epithelial cells, forming a protective barrier that surrounds your body and helps protect its internal environment from external threats.

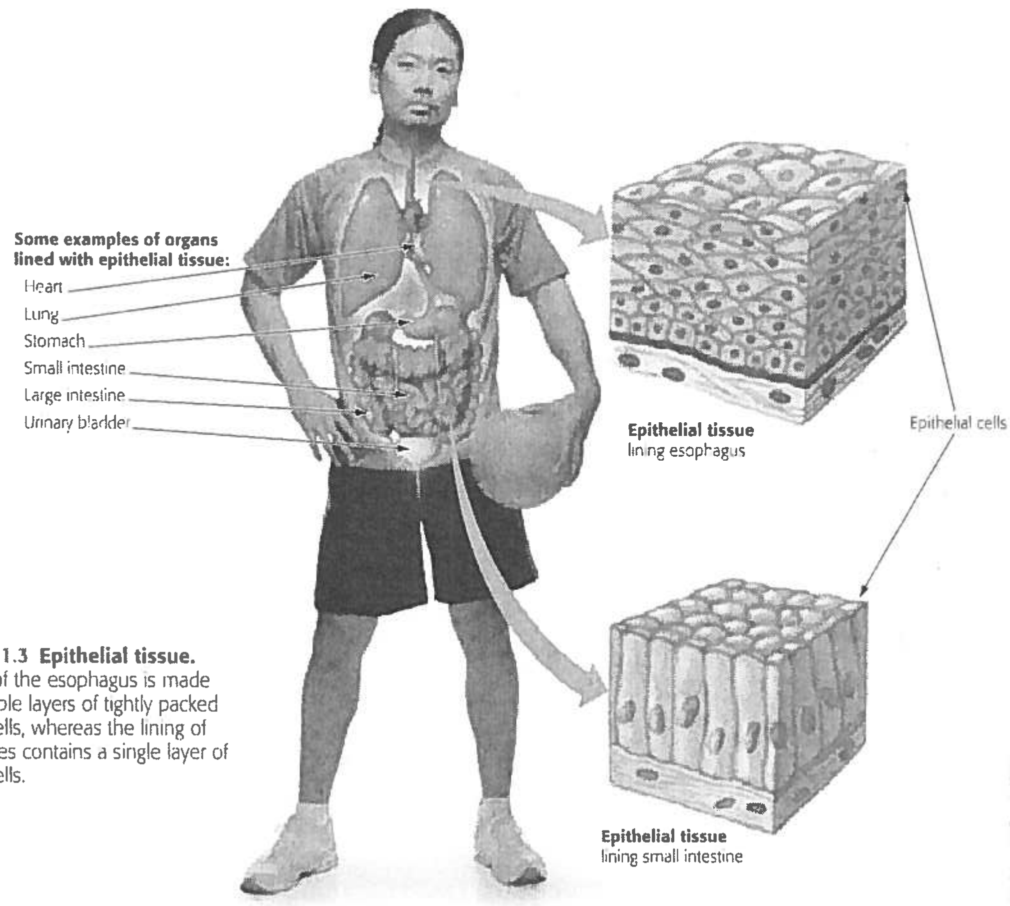
The body continuously renews the cells of epithelial tissue, shedding old cells and growing new ones. For example, cells of the epidermis continuously fall off and are renewed about every two weeks. Such turnover requires rapid cell division, which increases the risk of an error in cell division that leads to cancer. And compared with other body tissues, epithelium that contacts the environment directly is exposed to much higher levels of carcinogens (smoke in the lungs and UV light on the skin, for example). Consequently, about 80% of all cancers (including skin, lung, and breast cancer) arise in epithelial tissue. Cancers of the epithelium are called carcinomas.

Connective Tissue

In contrast to epithelium, with its tightly packed cells, **connective tissue** has a sparse population of cells scattered throughout a jellylike material called the **extracellular matrix**. The matrix consists of a web of protein fibers embedded in a liquid (as in blood), jelly (as in fat tissue), or solid (as in bone).

The structure of connective tissue corresponds to its function: to bind and support other tissues. For example, the epithelial tissue of your skin (epidermis) lies on top of a layer of connective tissue called the dermis, which contains the blood vessels and extracellular fluids that nourish the epidermis.

Figure 21.4 illustrates six of the major types of connective tissue. The most widespread connective tissue in the body of vertebrates (animals with backbones, including humans) is **loose connective tissue (Figure 21.4a)**. It binds epithelia to underlying tissues and holds organs in place, similar to the way that packing peanuts can prevent shipped merchandise from sliding around. This connective tissue is held together by a mesh of protein fibers that provide great strength and elasticity. For example, if someone pinches your cheek, it is protein fibers that



► **Figure 21.3 Epithelial tissue.** The lining of the esophagus is made up of multiple layers of tightly packed epithelial cells, whereas the lining of the intestines contains a single layer of epithelial cells.

keep your flesh in place and allow it to quickly snap back. A decrease in production of one of these proteins (collagen) as we age can result in skin wrinkles; some people inject collagen in an attempt to restore smooth skin.

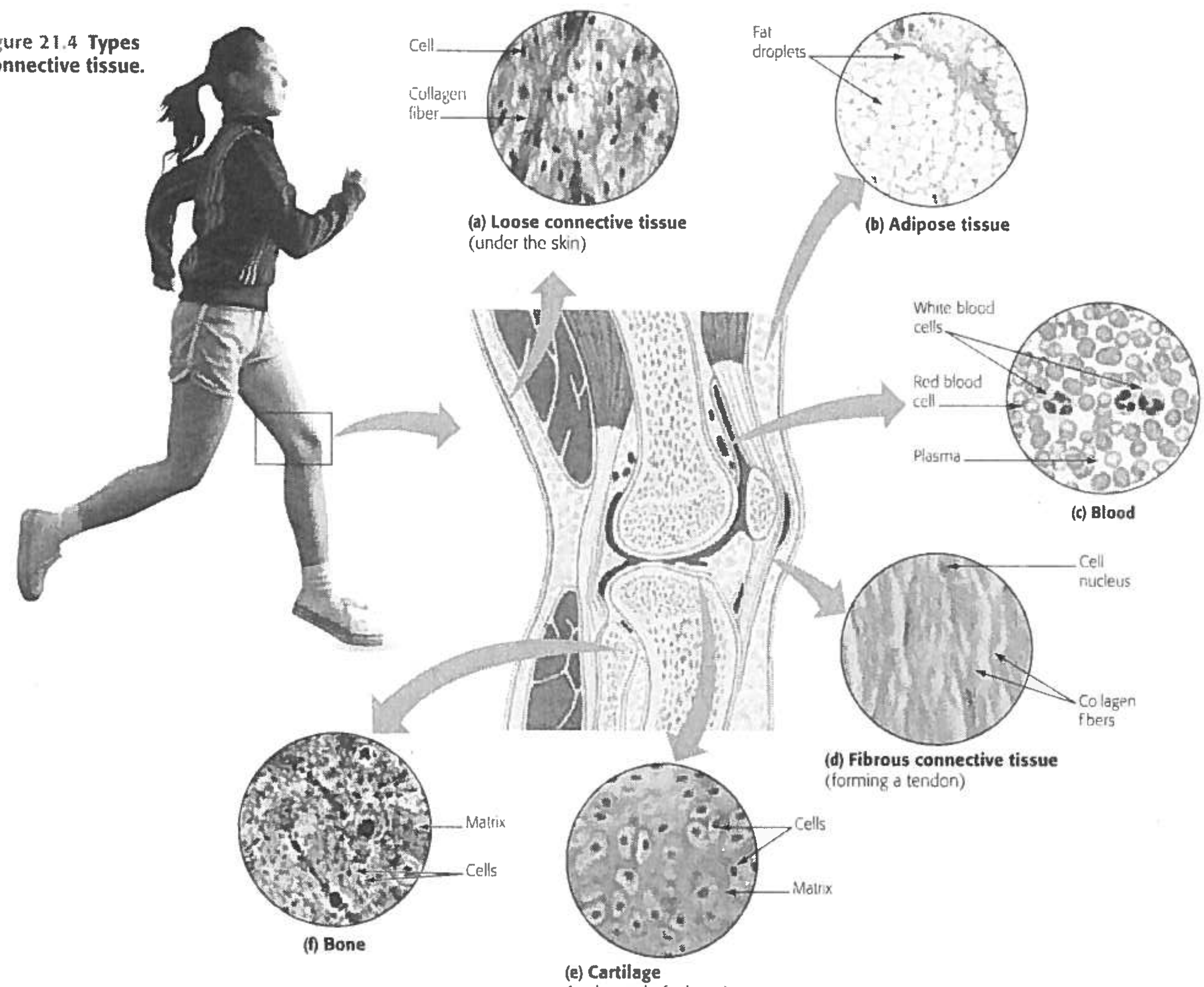
Adipose tissue stores fat in closely packed cells (**Figure 21.4b**). This tissue stockpiles energy while also padding and insulating the body. Each adipose cell contains a large globule of fat (mostly triglycerides—see Figure 3.11b); the cell swells when fat is stored and shrinks when fat is used for energy. Gaining body fat involves increasing the size of your fat cells, not creating new fat cells.

Blood is a connective tissue consisting of red and white blood cells suspended in a liquid called plasma (**Figure 21.4c**). Blood functions mainly in transporting substances from one part of the body to another and also plays a major role in immunity.

The other three types of connective tissue have cells suspended in dense matrices. **Fibrous connective tissue** has a dense matrix of collagen. It forms tendons, which attach muscles to bones, and ligaments, which join bones together at joints (**Figure 21.4d**). The matrix of **cartilage** is strong but flexible (**Figure 21.4e**). Use your finger to flip your outer ear, and you'll get the idea of how cartilage functions as a flexible, boneless skeleton. The cartilaginous fishes—which include sharks and rays—have skeletons made entirely from cartilage. Cartilage is often found at the end of bones where it forms shock-absorbing pads. Cartilage has no blood vessels, so injuries to it (football knee injuries, for example) tend to heal very slowly, if at all. **Bone** is a rigid connective tissue with a matrix of collagen fibers hardened with deposits of calcium salts. This combination makes bone hard without being brittle (**Figure 21.4f**).

Why are knee injuries often long-lasting?

► **Figure 21.4 Types of connective tissue.**



(a) Loose connective tissue (under the skin)

(b) Adipose tissue

(c) Blood

(d) Fibrous connective tissue (forming a tendon)

(e) Cartilage (at the end of a bone)

(f) Bone

Muscle Tissue

Muscle is the most abundant tissue in most animals. In fact, what we call "meat" on the menu is mostly animal muscle. **Muscle tissue** consists of bundles of long, thin, cylindrical cells called muscle fibers. Each cell has specialized proteins arranged into a structure that contracts (pulls in) when the cell is stimulated by a signal from a nerve. Humans and other vertebrates have three types of this contractile tissue, each with a slightly different structure: skeletal muscle, cardiac (heart) muscle, and smooth muscle.

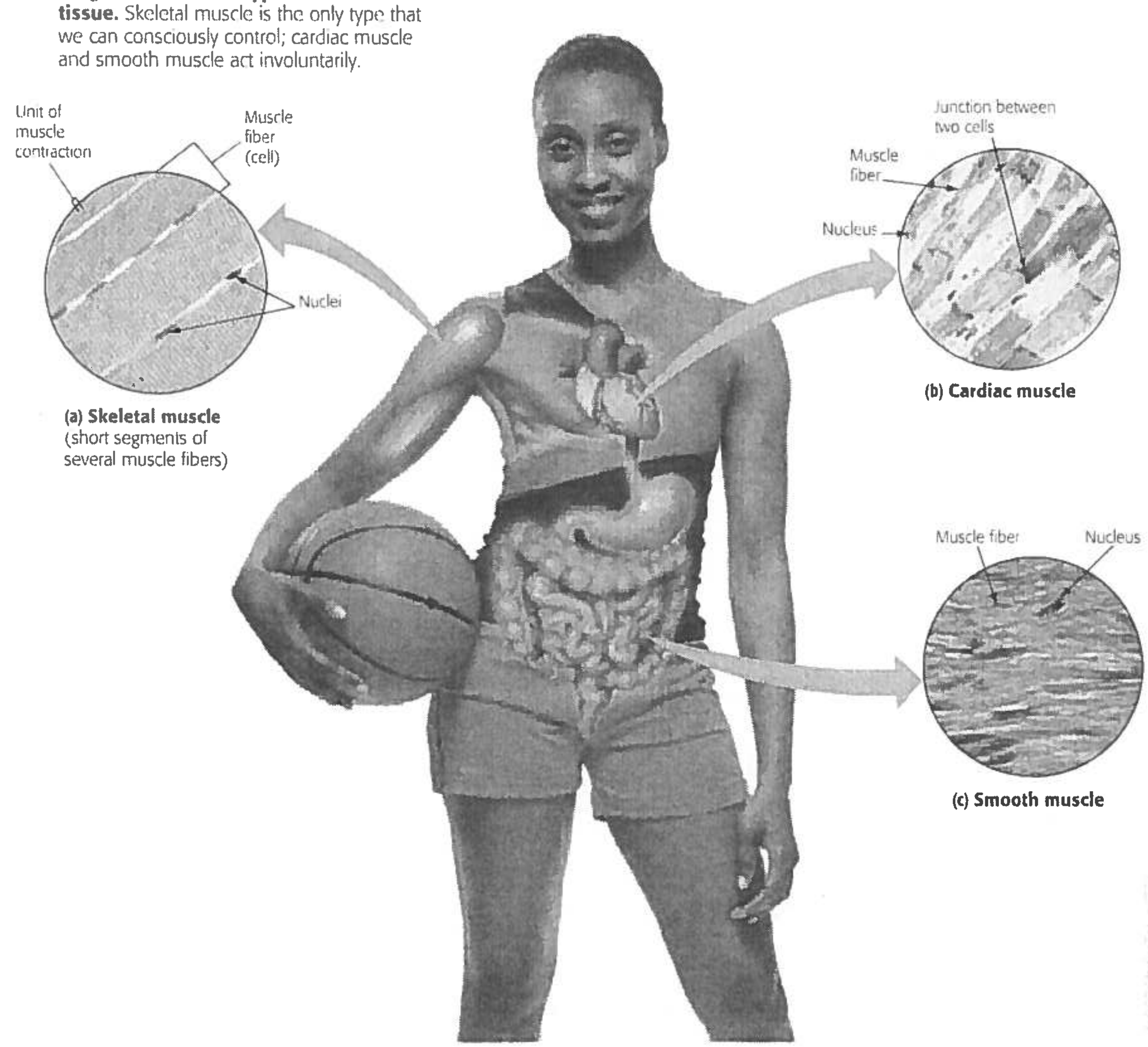
Skeletal muscle is attached to your bones by tendons and is responsible for your voluntary movements, such as walking and talking (**Figure 21.5a**). This type of muscle is said to be striated (striped) because the contractile proteins form a banded pattern. Adults have a fixed number of these cells. Weight training does not increase the number of muscle cells but instead enlarges those already present.

What effect does working out have on your muscles?

Cardiac muscle is found only in heart tissue (**Figure 21.5b**). The contraction of the cardiac muscle produces the heartbeat. Cardiac muscle cells are branched and joined to one another, appearing like one large interconnected mass of muscle. This structure allows the contraction signal to be propagated quickly to all muscle cells at once, producing a coordinated beat. Cardiac muscle is an involuntary muscle, meaning that your heart contracts without any conscious control on your part.

In contrast to skeletal muscle and cardiac muscle, **smooth muscle** is named for its lack of obvious stripes (**Figure 21.5c**). Found in the walls of such organs as the intestines and blood vessels, smooth muscle is involuntary. For example, you have no control over the dilation of your blood vessels in response to heat, a response that causes you to flush. Smooth muscle contracts more slowly than skeletal muscle, but it can remain contracted for a longer time.

▼Figure 21.5 Three types of muscle tissue. Skeletal muscle is the only type that we can consciously control; cardiac muscle and smooth muscle act involuntarily.

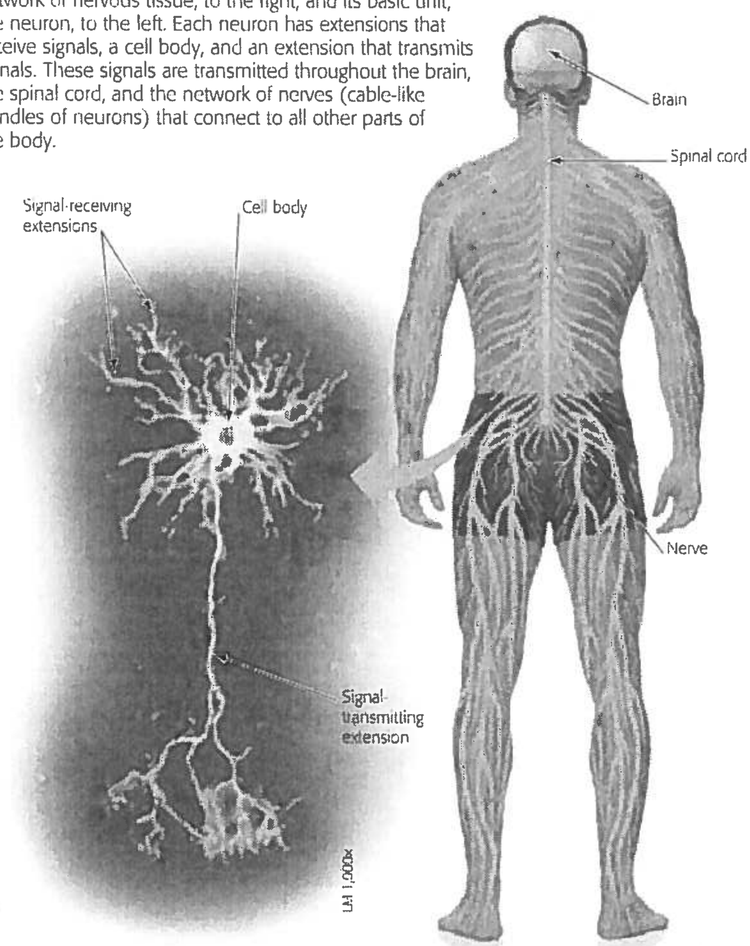


Nervous Tissue

Most animals are active creatures that respond rapidly to stimuli from their environment. For example, if you touch a very hot object, your arm quickly jerks away. This response requires information to be relayed from one part of the body to another. It is **nervous tissue** that makes such communication possible. Nervous tissue is found in your brain and spinal cord, as well as in the nerves that connect them to all other parts of your body.

The basic unit of nervous tissue is the **neuron,** or nerve cell **(Figure 21.6)**. With their long extensions, neurons can transmit electrical signals very rapidly over long distances. For example, neurons in the sciatic nerve of your leg may be as long as 1 m (3.3 feet), running all the way from the base of your spinal cord to the tips of your toes. You are wired for action—and for thinking, since it is the network of neurons in your brain that functions as your mind. ☑

▼Figure 21.6 Nervous tissue. Here you see the body's network of nervous tissue, to the right, and its basic unit, the neuron, to the left. Each neuron has extensions that receive signals, a cell body, and an extension that transmits signals. These signals are transmitted throughout the brain, the spinal cord, and the network of nerves (cable-like bundles of neurons) that connect to all other parts of the body.



Organs and Organ Systems

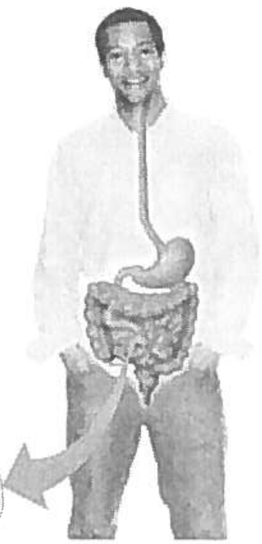
After tissues, the next level in the structural hierarchy is the organ. An **organ** consists of two or more tissues packaged into one working unit that performs a specific function. Your heart, brain, and small intestine are examples of organs. At each level of the hierarchy, functions emerge from the collective interaction of the structures at lower levels. An organ performs functions that none of its component tissues can carry out alone.

To see how multiple tissues coordinate a single organ, examine the layered arrangement of tissues in the wall of the small intestine in **Figure 21.7**. The inside wall is lined with epithelial tissue (top layer of cells in figure) that secretes mucus. Underneath this layer are two layers of connective tissue—one containing blood capillaries and lymph vessels—separated by two layers of smooth muscle. A final layer of epithelial tissue forms the outside surface. Neurons regulate the rhythmic contractions of the intestinal muscles, propelling food.

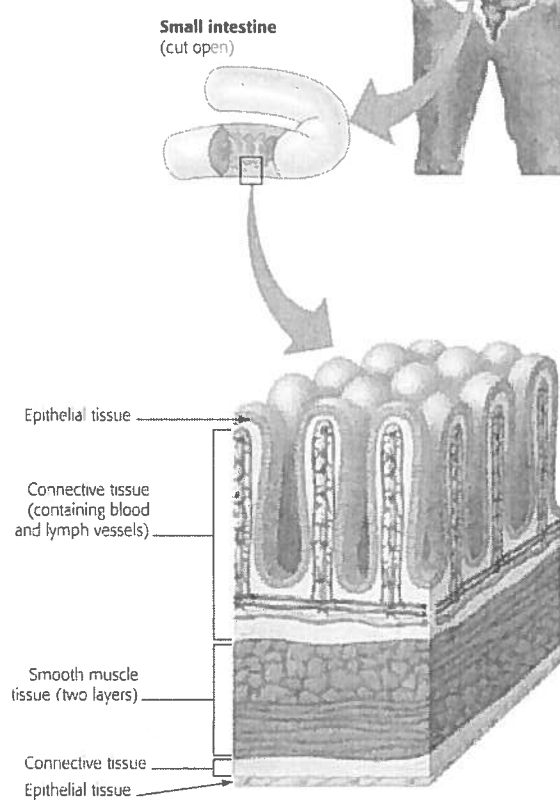
☑ CHECKPOINT

Name the four types of tissue found in most organs.

Answer: epithelial, connective, muscle, and nervous



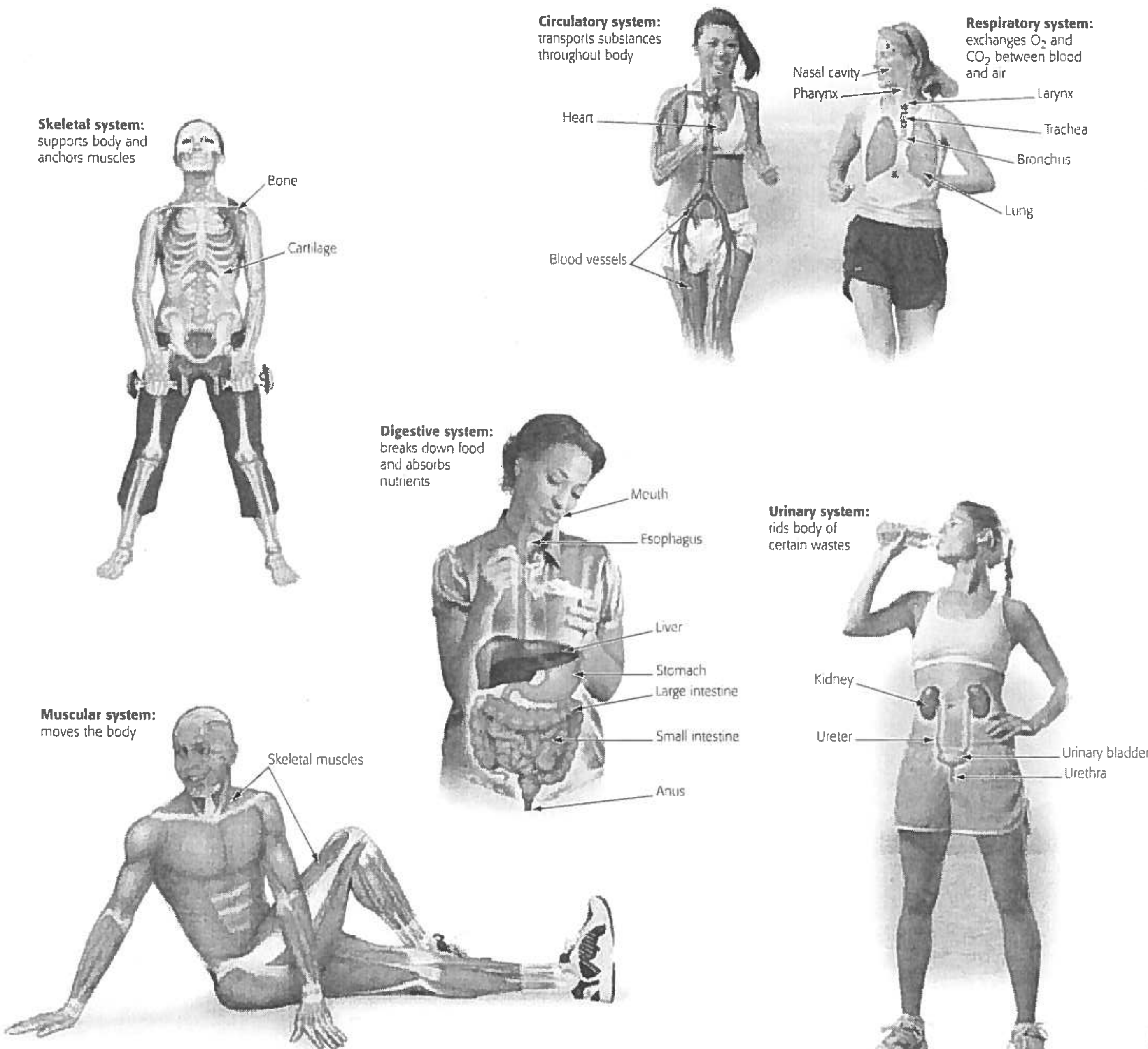
► Figure 21.7 Tissue layers of the small intestine, an organ.



The organs of humans and most other animals are organized into **organ systems**, teams of organs that work together to perform vital body functions. The components of an organ system can be physically connected or they can be dispersed within the body. An example of an organ system is your circulatory system, which transports materials throughout your body. Its main organs are the heart and blood vessels (arteries, veins, and capillaries). **Figure 21.8** presents an overview of 11 major organ systems in vertebrates.

An organism depends on the coordination of all its organ systems for survival. For instance,

▼Figure 21.8 Organ systems of a vertebrate.

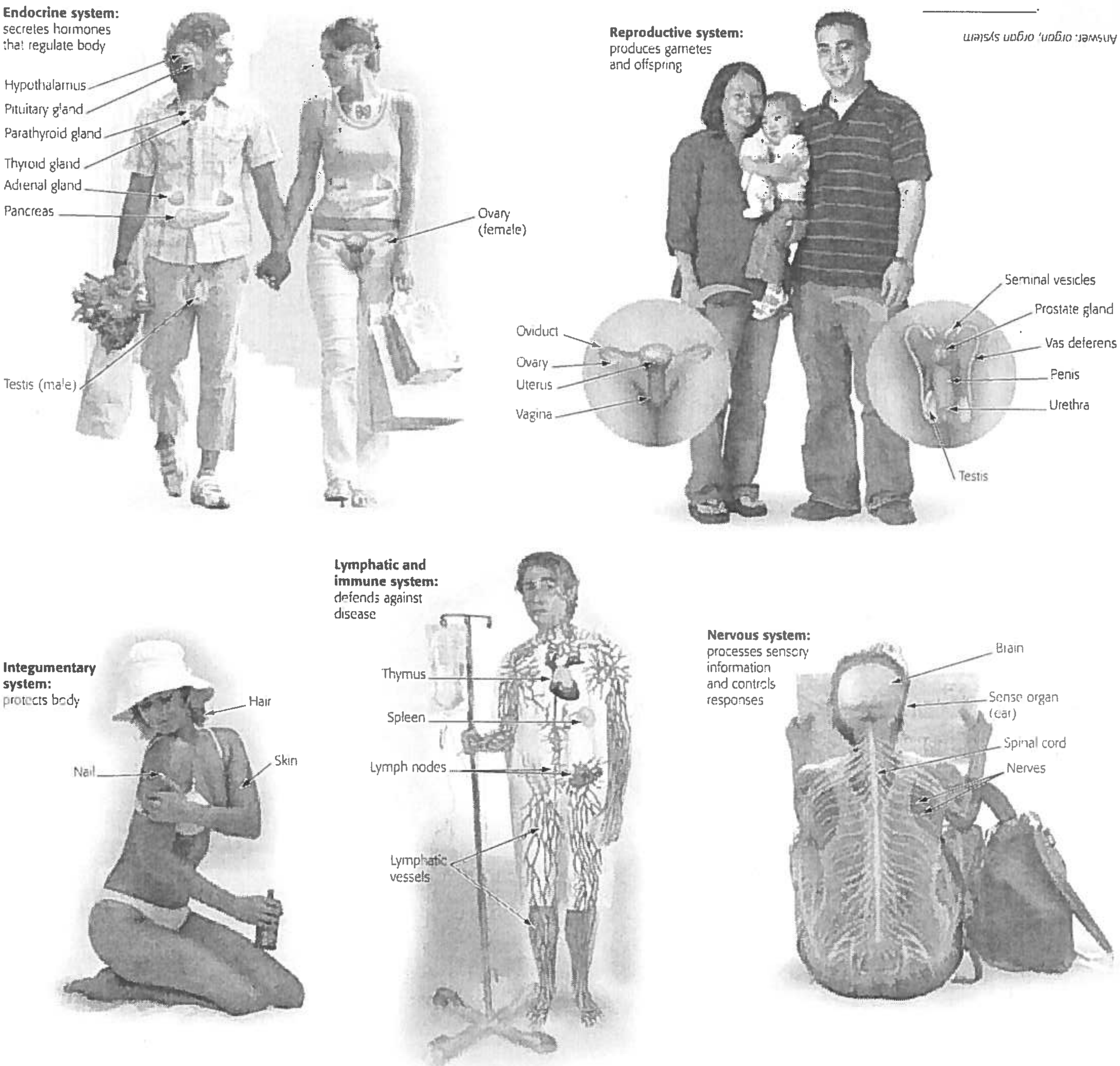


the action of muscle cells can produce body heat, raising your internal temperature. Cells within your nervous system can sense the temperature change and send signals that cause blood vessels of your circulatory system to widen, releasing heat. The failure of any organ system will jeopardize the entire animal because organ systems are so interwoven and dependent on each other. Your body is a whole, living unit that is greater than the sum of its parts. In the next section, we'll look at how the body's organ systems interact with the external environment. ☑

☑ CHECKPOINT

Your stomach is a(n) ____________, whereas your digestive system is a(n) ____________.

Answer: organ; organ system



Exchanges with the External Environment

Most animals are covered with a protective layer that separates the external world from the internal chemical environment. This does not mean, however, that an animal encloses itself in some sort of protective bubble, isolated from the harsh world outside. Just as a car engine will quickly stall if the air intake is clogged, your body will quickly shut down if deprived of outside oxygen. Every organism is an **open system** that continuously exchanges chemicals and energy with its surroundings. You eat, breathe, defecate, urinate, sweat, and radiate heat—all examples of how you operate as an open system. And the exchange of materials extends down the hierarchy to each individual cell: Nutrients and oxygen must enter every living cell, and carbon dioxide and other wastes must exit.

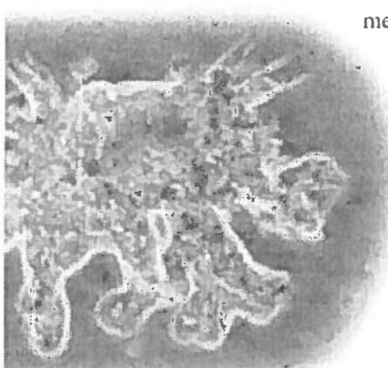
Why doesn't a parasitic tapeworm require a digestive system?

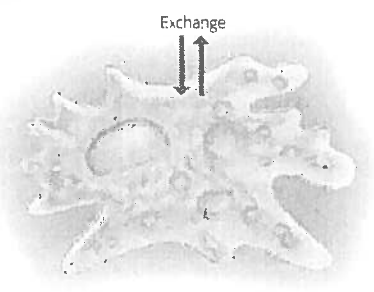
An animal's size and shape affects its exchanges with its surrounding environment. Every living cell of an animal's body must be bathed in a watery solution, partly because substances must be dissolved in water to cross cell membranes. In a single-celled amoeba (a type of protist), every part of its body borders the outside world, where exchange with the watery environment can occur **(Figure 21.9a)**.

Exchange with the environment is more complicated for multicellular animals. Each cell in a multicellular organism has a plasma membrane where exchange of materials can occur. But this exchange only works if all the cells of the animal have access to a suitable watery environment. A hydra (a simple pond-dwelling relative of jellies) has a body wall only two cell layers thick **(Figure 21.9b)**. Both layers of cells are bathed in pond water, which enters the digestive sac through the mouth. Every cell of the hydra can thus exchange materials through direct contact with the watery environment. A flat body shape is another way of maximizing exposure to the environment. For instance, a tapeworm may be several meters long, but because it is very thin, most of its cells are bathed in the body fluid of the worm's host, from which it obtains nutrients directly.

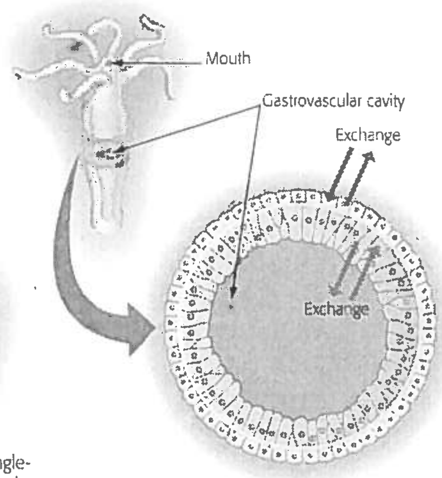
Simple body shapes do not allow for much complexity in internal organization. But animals with more complex body forms face the same basic problem: Every living cell in the body must be bathed in fluid and have access to resources from the outside environment. Complex animals have evolved extensively folded or branched internal surfaces that maximize surface area for exchange with the immediate environment. For example, your lungs, which exchange oxygen and carbon dioxide with the air you breathe, are not shaped like big balloons but like millions of tiny balloons at the tips of finely branched air tubes **(Figure 21.10)**. The epithelium of the lungs has a very large total surface area—about the size of a tennis court.

▼Figure 21.9 Contact of simple organisms with the environment.





(a) Single cell. The entire surface area of a single-celled organism, such as this amoeba, contacts the environment. Because of its small size, the organism has a large surface area (relative to its volume) through which it exchanges materials with the external world.



(b) Two cell layers. Although a hydra is multicellular, each one of its cells touches an aqueous envrionment. The body has only two cell layers, both exposed to water.

▼Figure 21.10 The branched surface area of the human lung. This plastic model shows the tiny air tubes of the lungs (white) and the thin blood vessels (red) that transport gases between the heart and lungs.

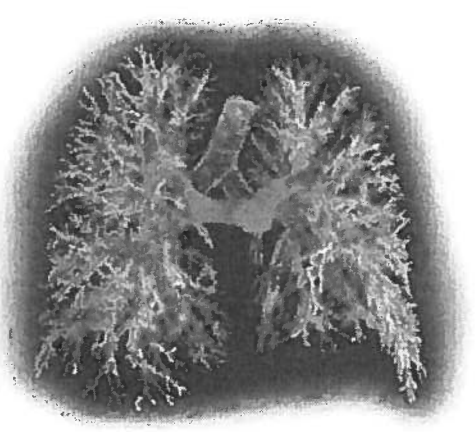
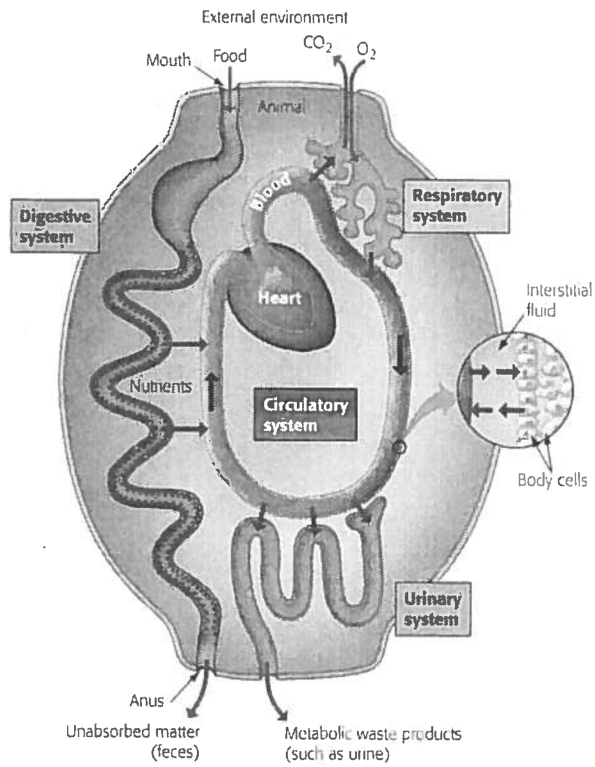


Figure 21.11 shows a schematic model of an animal body, highlighting the three organ systems—digestive, respiratory, and urinary—that exchange materials with the external environment. Notice also the vital role of the circulatory system: It connects to nearly every organ system as it transports needed materials from the environment to the body's tissues and carries wastes away. Looking at the figure, you can see how nutrients that are absorbed from the digestive tract are distributed throughout the body by the circulatory system. The heart that pumps blood through the circulatory system requires nutrients absorbed from food by the digestive tract and also oxygen (O_2) obtained from the air by the respiratory system. And absorption of nutrients inevitably produces wastes that must be excreted by the urinary system. The circulatory system thereby provides an internal conduit that joins the systems that connect with the outside world. ☑



► **Figure 21.11 Exchange between the external environment and the internal environment of complex animals.** The blue arrows indicate the exchange of materials between the circulatory system and three other systems and between the circulatory system and body cells.

☑ CHECKPOINT

Is your body an open or closed system? Why?

Answer: Your body is an open system, because the digestive, respiratory, and urinary systems are in direct contact with the external environment.

Regulating the Internal Environment

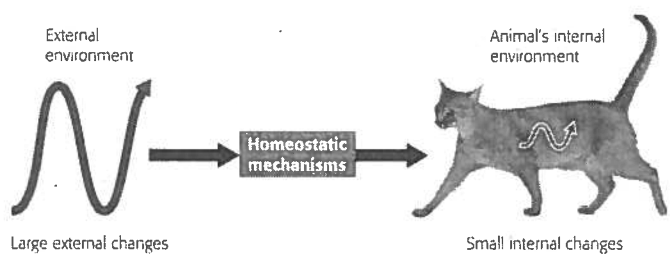
In this section, you'll learn how animals adjust to a changing environment. We'll look in particular at how they regulate temperature and control the movement of water and solutes.

Homeostasis

One of the body's most important functions is to stay relatively unchanged even when the world around it changes. The internal environment of vertebrates includes the **interstitial fluid** that fills the spaces between cells and exchanges nutrients and wastes with microscopic blood vessels (see Figure 21.11). It is important that the composition of the interstitial fluid remain relatively constant no matter what occurs in the outside world.

Homeostasis, which literally means "steady state," is the tendency to maintain relatively constant conditions in the internal environment even when the external environment changes. In the face of large external changes, the mechanisms of homeostasis normally maintain internal conditions within a range that the animal's metabolism can tolerate (**Figure 21.12**). For example, your internal body temperature normally fluctuates by less than a degree, whether you are making an angel in the cold winter snow or a cannonball into a pool in the hot summer sun. Losing the ability to maintain homeostasis can have significant health consequences. Diabetes, for example, is a loss of glucose homeostasis in the blood.

▼ **Figure 21.12 Homeostasis.**



Actually, the internal environment of an animal always fluctuates slightly in response to internal and external changes. Blood glucose levels, for example, rise after a meal. Homeostasis is a dynamic state, an interplay between outside forces that tend to change the internal environment and internal control mechanisms that oppose such changes. Changes do occur, but they generally stay within a range that is tolerable for living cells. In addition, there are times during the development of an animal when major changes in the internal environment are programmed to occur. For example, the balance of hormones in human blood changes radically during puberty or pregnancy, and body temperature may rise a few degrees in response to a bacterial infection.

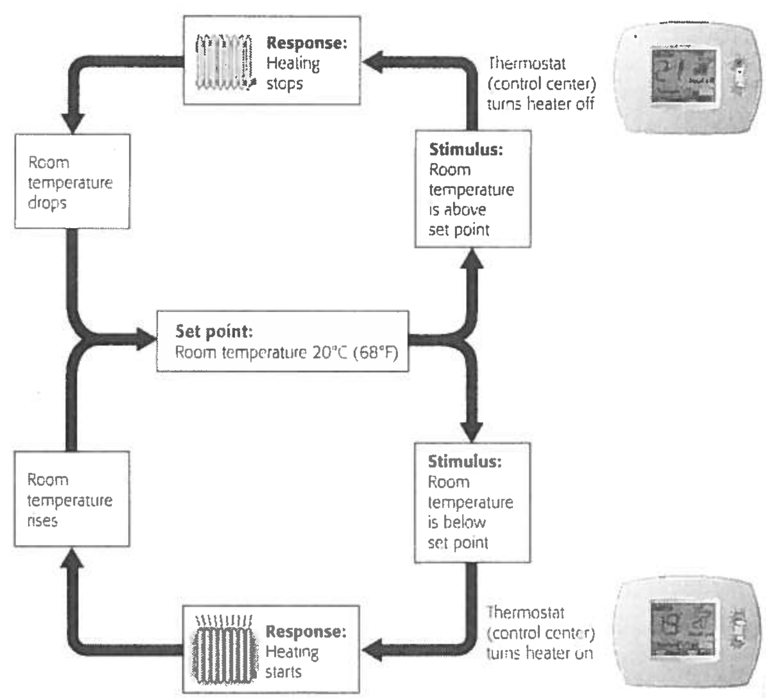
Negative and Positive Feedback

Most mechanisms of homeostasis depend on a principle called **negative feedback**, a form of regulation in which the results of a process inhibit that same process. **Figure 21.13** illustrates the concept of negative feedback with an example of household homeostasis, the control of room temperature. During the winter, a home heating system maintains a relatively constant temperature inside the house despite drastic changes that may occur outside. A key component of this system is a control center—a thermostat—that monitors temperature and switches the heater on and off. Whenever room temperature drops below the set point (the temperature at which the thermostat is set, 20°C in the figure), the thermostat switches the heater on (bottom pathway in Figure 21.13). When the temperature rises above the set point, the thermostat switches the heater off (top pathway). The basic principle of negative feedback is simple: The result (increased room temperature, for example) of a process (heating of the air) inhibits that very process (by switching the heater off). Negative feedback is the most common mechanism of homeostatic control in animals.

Less commonly, organisms use **positive feedback**, in which the results of a process intensify that same process. For example, during the labor that leads up to childbirth, chemical signals cause the muscles of the uterus to contract. This contraction stimulates the release of more such chemicals, which cause more contractions, and so on, in a positive-feedback loop of increasing intensity. The result is climactic muscle contractions that push the baby from the womb.

In the rest of this section, we'll examine several specific examples of homeostasis. We'll first discuss the control of temperature and the control of water gain and loss in a variety of animals. We'll then focus on the human urinary system—an organ system that performs several homeostatic roles. ☑

► Figure 21.13 An example of negative feedback: control of room temperature. This is an example of negative feedback because the result of the process (heat) shuts that process down.



☑ CHECKPOINT

When you flush a toilet, water begins to refill the tank. The rising water level lifts a float. When the float reaches a certain height, it stops more water from entering the tank. This is an example of what kind of homeostatic control? Why?

Answer: This is an example of negative feedback because the result of a process (water filling the tank) inhibits that same process.

Thermoregulation

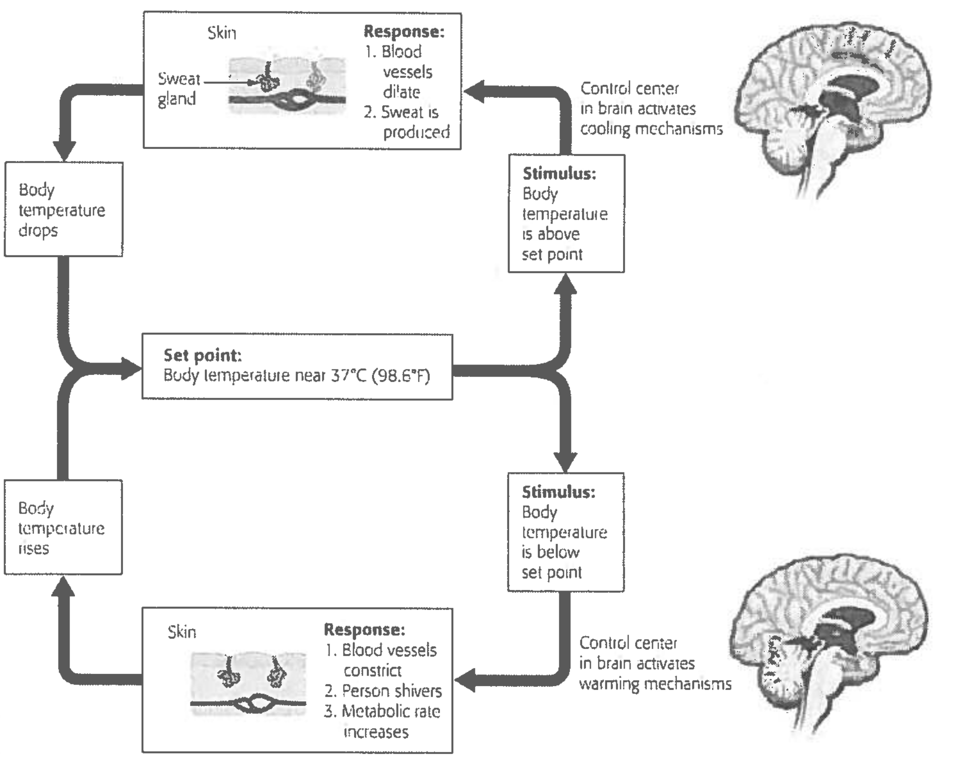
As you saw in the Biology and Society section, the maintenance of internal body temperature is important in animals. This homeostatic mechanism is called **thermoregulation**. As you walk from a warm building to the outside on a cold winter day, your body's temperature will barely fluctuate, despite the drastic change in temperature in the environment around you. The ability to maintain a body temperature substantially warmer than the surrounding environment is characteristic of **endotherms**, animals such as mammals and birds that derive most of their body heat from their own metabolism. In contrast, **ectotherms**, which include most invertebrates, fishes, amphibians, and nonbird reptiles, obtain their body heat primarily by absorbing it from their surroundings.

You have a number of structures and mechanisms that aid in thermoregulation. As shown in **Figure 21.14**, your brain has a control center that maintains your body temperature near 37°C (98.6°F). When your body temperature falls below normal, your brain's control center sends signals that trigger changes that will bring it back to normal: Blood vessels near your body's surface constrict (conserving heat) and muscles contract, causing you to shiver (producing heat). When body temperature gets too high, the control center sends signals to dilate the blood vessels near your skin and activate sweat glands, allowing excess heat to escape. Like a home controlled by a thermostat, the temperature of the body does not stay completely constant but fluctuates up and down within an acceptable range.

Why do you shiver when you are cold?

Fever, an abnormally high internal temperature, is a body-wide response that usually indicates an ongoing fight against infection. When your immune system cells encounter invading microbes, the cells release chemicals that travel through the bloodstream to your brain. These chemicals stimulate your brain's thermostatic control center to raise the body's internal temperature, producing a fever. Many people mistakenly believe that the invading microbes themselves cause a fever. In fact, the cause is usually the body's fight *against* the microbes. A fever of more than 40°C (104°F) may be life-threatening because a temperature that high can damage body proteins. A moderate fever of 38–39°C (100–102°F), however, discourages bacterial growth and speeds the body's internal defenses. A moderate fever thus helps protect the body's internal environment against potentially harmful invaders from the external environment.

We are endotherms and so can generate body heat to warm ourselves. Ectotherms generally cannot. But there are exceptions to this rule, as we'll see next in the Process of Science section. ☑



◄ **Figure 21.14 Thermoregulation in the human body.** By comparing this figure with Figure 21.13, you can see how similar negative feedback controls moderate the temperatures of a room and your body. The control center for body temperature is located in the brain.

☑ CHECKPOINT

Name two features of the human body that help release heat and two features that help keep the body warm.

Answer: Examples include sweating and dilation of blood vessels to release heat; shivering and constriction of blood vessels to keep the body warm.

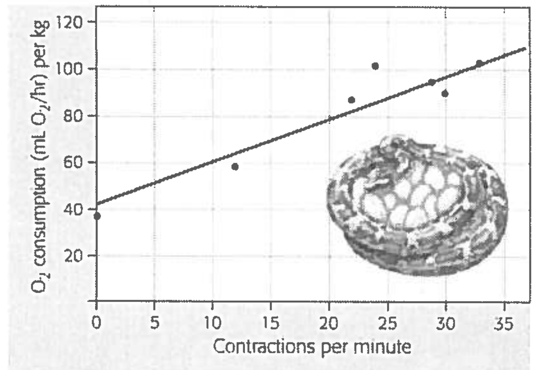
Controlling Body Temperature THE PROCESS OF SCIENCE

How Does a Python Warm Her Eggs?

As just described, ectotherms usually absorb heat from their surroundings. Under certain circumstances, however, some ectotherms can generate their own body heat. An example is the Burmese python (*Python molurus bivittatus*), a very large snake native to the rain forests of southeastern Asia. Like most snakes, it reproduces by laying eggs. Researchers at the Bronx Zoo, in New York City, made the **observation** that a female Burmese python incubating her eggs wraps her body around them, raises her body temperature, and frequently contracts the muscles in her coils. They formed the **hypothesis** that the muscle contractions elevate the snake's body temperature.

To test their hypothesis, they performed a simple **experiment**. They placed a python and her eggs in a chamber. As they varied the chamber's temperature, they monitored the python's muscle contractions and oxygen uptake, a measure of her rate of cellular respiration. Their **results** showed that the python's oxygen consumption increased when the temperature in the chamber decreased. Her oxygen consumption also changed with the rate of muscle contraction (**Figure 21.15**). Because oxygen consumption generates heat through cellular respiration and increases with the rate of muscle contraction, the researchers concluded that the muscle contractions were the source of the Burmese python's elevated body temperature during egg incubation. As you'll see in the Evolution Connection section, such behavior is just one of many temperature-regulating adaptations that have evolved in animals.

▼**Figure 21.15 Oxygen consumed by a Burmese python as it constricts its muscles.**



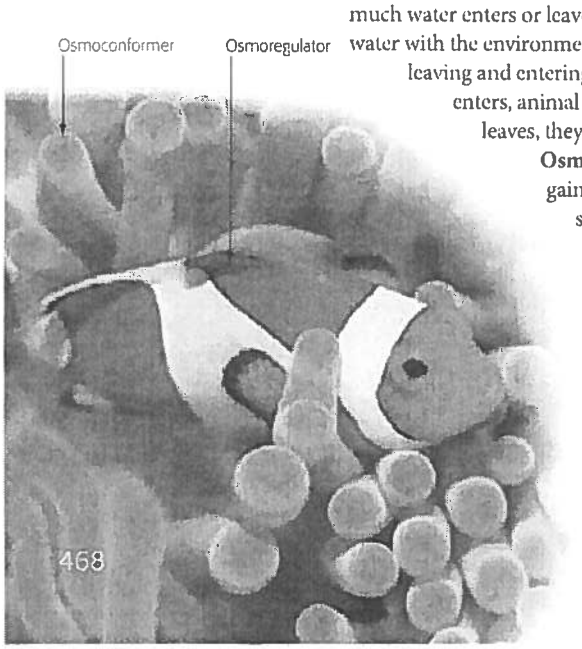
Osmoregulation

Living cells depend on a precise balance of water and solutes (dissolved substances). Whether an animal inhabits land, fresh water, or salt water, its cells cannot survive if too much water enters or leaves. That is, a cell may exchange water with the environment as long as the total amount leaving and entering is the same. If too much water enters, animal cells will burst; if too much leaves, they will shrivel and die.

Osmoregulation is the control of the gain or loss of water and dissolved solutes, such as the ions of NaCl and other salts. Osmoregulation is based largely on regulating solutes because water follows the movement of solutes by osmosis. Osmosis occurs whenever two solutions separated by a permeable membrane differ in their total solute concentrations (see Figure 5.13). There is always a net movement of water from the solution with lower solute concentration to the one with higher solute concentration.

A variety of mechanisms have evolved that maintain water balance in aquatic animals. Most marine invertebrates—such as lobsters, scallops, and jellies—are **osmoconformers**, meaning that their internal and external environments have similar solute concentrations. Osmoconformers do not need special mechanisms to prevent a net gain or loss of water. In contrast, all freshwater animals and most of the marine vertebrates are **osmoregulators**: They must actively regulate water loss and gain (**Figure 21.16**).

As an example, let's compare osmoregulation in freshwater and saltwater fish. Both kinds of fish have about the same concentration of solutes in their blood despite their very different environments: Saltwater fish have less salt in their tissues than the water they swim in, while freshwater fish have more. How do they achieve this control? In fresh water, the external solute concentration is low, so water enters the fish



◄**Figure 21.16 Osmoconformers and osmoregulators.** Most marine invertebrates (such as the sea anemone whose tentacles are visible here) are osmoconformers, which have water concentrations similar to their surroundings. Most marine vertebrates (such as this clown fish) are osmoregulators, which use mechanisms to maintain water balance.

by osmosis. To compensate, freshwater fish take up solutes via the digestive system and gills and produce large amounts of dilute urine. In contrast, osmoregulators that live in salt water lose water by osmosis. In response, saltwater fish take in water by drinking, pump out ions via the gills, and produce only small amounts of concentrated urine.

All land animals are osmoregulators. Most land animals gain water from eating and drinking and lose it through urinating, defecating, breathing, and perspiring. The primary challenge facing land-dwelling osmoregulators is to avoid becoming dehydrated. As we'll see in the next section, our kidneys play a major role in regulating water balance. ☑

Homeostasis in the Urinary System

The human urinary system plays a central role in forming and excreting waste-carrying urine while regulating the amount of water and solutes in body fluids. The main processing centers are the two kidneys. Each is a compact organ, a bit smaller than a fist, located on either side of the abdomen. The kidneys contain nearly 100 miles of thin tubes called **tubules** and an intricate network of capillaries (tiny blood vessels). Every day, all of your blood passes through the capillaries of your kidneys hundreds of times. As the blood circulates, a fraction of it is filtered, and the plasma (the liquid portion) enters the kidney tubules. Once there, the plasma is called **filtrate**. The filtrate contains valuable substances that need to be reclaimed (such as water and glucose) and other substances that need to be disposed of. Chief among the waste products to be excreted is urea, a nitrogen-containing compound produced from the breakdown of proteins and nucleic acids. Humans must dispose of urea, but we cannot simply excrete all of the filtrate as urine; if we did, we would lose vital nutrients and dehydrate rapidly. Instead, our kidneys refine the filtrate, concentrating the wastes and returning most of the water and useful solutes to the blood.

The anatomy of the human urinary system is shown in Figure 21.17. Starting with the whole system in **Figure 21.17a**, blood to be filtered enters each kidney via a blood vessel called the renal artery. Filtered blood leaves the kidney in the renal vein. **Figure 21.17b** shows a cutaway view of a kidney. Within the kidney, the renal artery branches into millions of thin blood vessels. **Figure 21.17c** shows one branch of the renal artery supplying blood to a nephron via a network of capillaries. A **nephron** consists of a tubule and its associated blood vessels. Each kidney contains about a million nephrons.

The nephrons carry out the functions of the urinary system. Blood pressure forces water and solutes from the blood through a filter at the start of the nephron tubule, creating filtrate. As the filtrate then passes through the tubule, water and needed nutrients are reabsorbed into the bloodstream and wastes are secreted into the filtrate. The filtrate becomes more and more concentrated, resulting in a relatively small quantity of **urine**. At the end of the tubule, urine leaves the nephron via a collecting duct. Urine collects in the kidney and then leaves via the **ureter**. Urine is stored in the **urinary bladder** (visible in Figure 21.17a). Periodically, urine is expelled from the urinary bladder via the **urethra**, a tube that empties near the vagina in females and through the penis in males.

☑ CHECKPOINT

Name two ways that water enters your body and four ways that water leaves your body.

Answer: Water enters via eating and drinking and leaves via breathing, sweating, urinating, and defecating.

▼ Figure 21.17 Anatomy of the human urinary system.

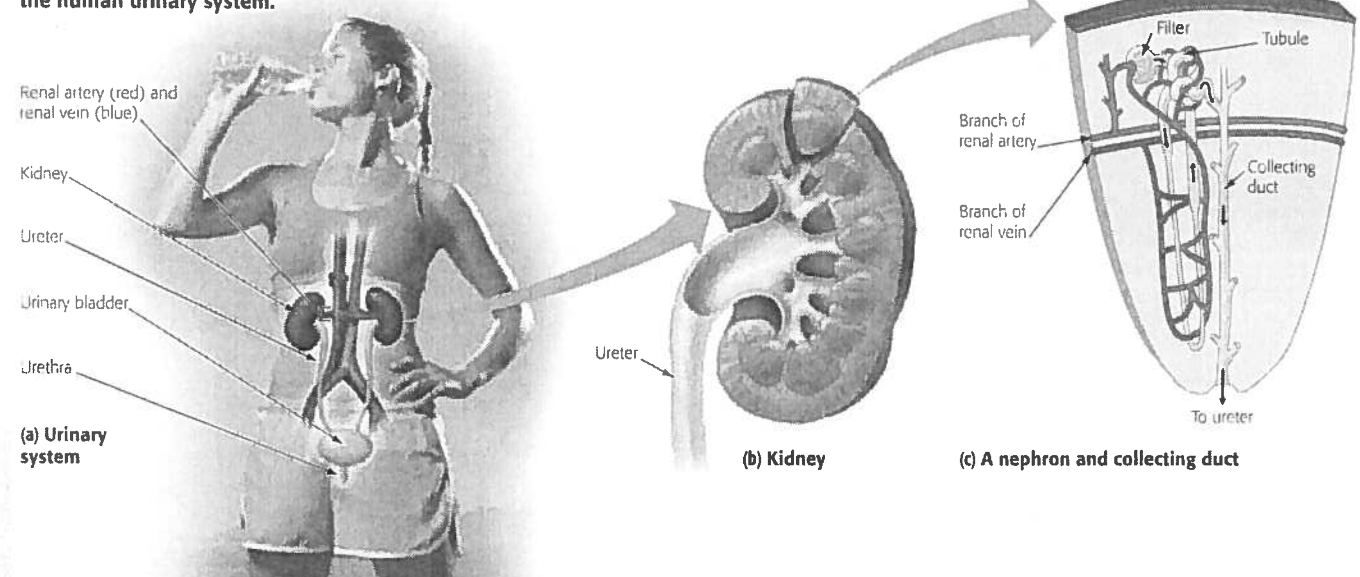


Figure 21.18 summarizes the functions performed by each nephron. First, during **filtration**, water and other small molecules are forced from the blood through a capillary wall into the beginning of a kidney tubule, forming filtrate. Next, in **reabsorption**, water and valuable solutes are reclaimed from the filtrate and returned to the blood. In **secretion**, certain substances, such as some ions and drugs, are transported into the filtrate. What remains after filtration, reabsorption, and secretion is the urine. Finally, in **excretion**, urine passes from the kidneys to the outside.

Why is kidney failure inevitably fatal if untreated?

The body controls its concentration of water and dissolved molecules through hormones that act on the kidney's nephrons. When the solute concentration of body fluids rises too high (indicating that not enough water is present), the brain increases levels of a hormone called ADH (antidiuretic hormone) in the blood. This hormone signals the nephrons to reabsorb more water from the filtrate, effectively increasing the body's water content. Conversely, when body fluids become too dilute, blood levels of ADH drop, the kidneys reabsorb less water, and the excreted urine becomes much more dilute. This is why your urine is very clear after you have been drinking a lot of water. Diuretics, such as alcohol, are substances that inhibit the release of ADH and therefore cause excessive urinary water loss. Drinking alcohol will make you urinate more frequently, and the resulting dehydration contributes to the symptoms of a hangover.

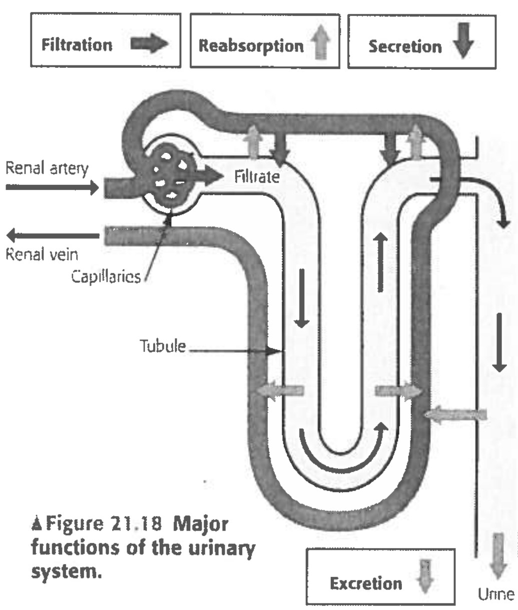
Kidney failure, the inability of the kidneys to filter blood, can be caused by injury, illness (such as high blood pressure or diabetes), or prolonged use of pain relievers (including over-the-counter medicines such as aspirin), alcohol, or other drugs. If the kidneys fail, the body is unable to rid itself of wastes. A person with one functioning kidney can lead a normal life, but if both kidneys fail, the buildup of toxic wastes will lead to certain and rapid death. One option is to place the person on **dialysis**, filtration of the blood by a machine that mimics the action of a nephron (**Figure 21.19**). Blood from an artery enters a series of selectively permeable tubes. Urea and excess fluids pass from the blood into a dialyzing solution, while necessary salts and other substances transfer the opposite way. The machine discards the used dialyzing solution as wastes accumulate. Dialysis treatment is life sustaining for people with kidney failure, but it is costly, takes a lot of time (about 4–6 hours three times a week), and must be continued for life. Alternatively, a kidney from a living compatible donor (usually a relative) or a deceased organ donor can be transplanted into a person with kidney failure. Unfortunately, the number of people who need kidneys is much greater than the number of kidneys available, and the average wait for a kidney donation in the United States is three to five years.

Throughout our study of animal form and function in this unit, you will see many other examples of how mechanisms of homeostasis moderate changes in the internal environment despite larger fluctuations in the external environment. You will also see many other examples of what happens when homeostatic controls fail. ☑

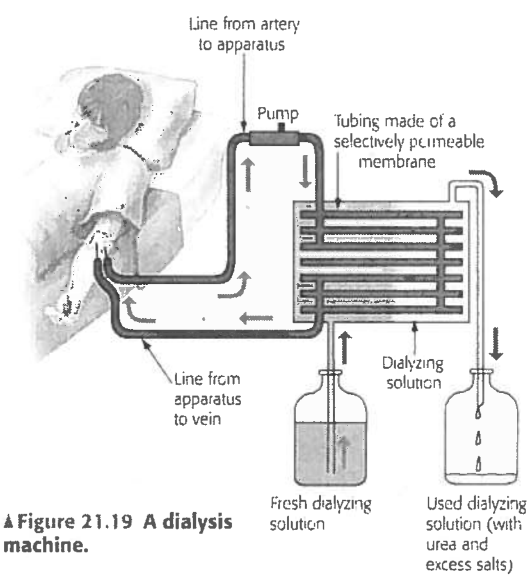
☑ CHECKPOINT

Name the four processes that occur as kidney tubules process blood and create urine.

Answer: filtration, reabsorption, secretion, excretion



▲Figure 21.18 Major functions of the urinary system.



▲Figure 21.19 A dialysis machine.

Adaptations for Thermoregulation

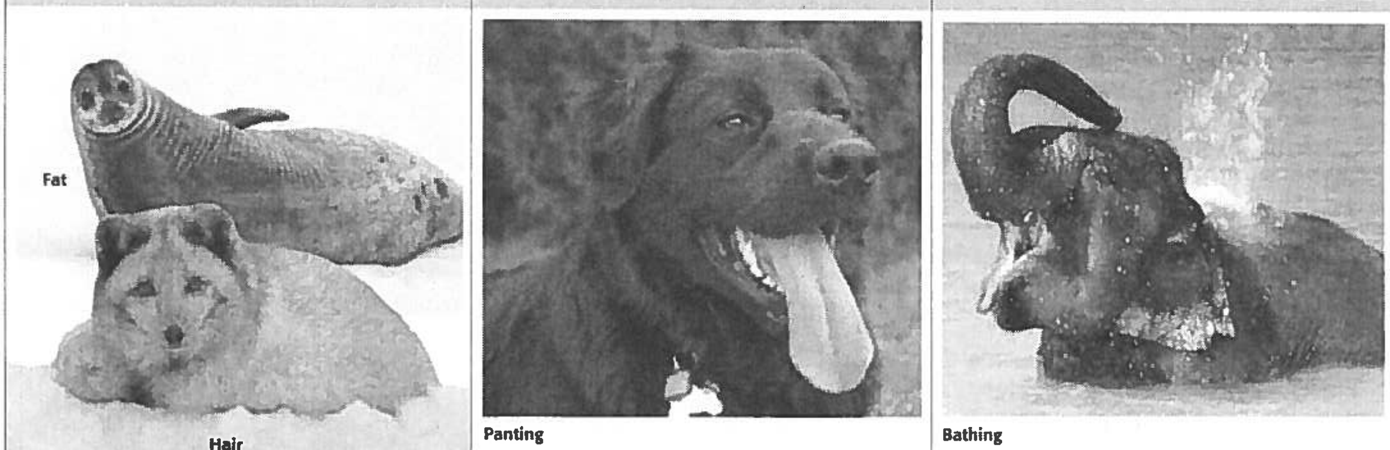
Natural selection has promoted a wide variety of adaptations—anatomical, physiological, and behavioral—that help animals cope with heat gained from or lost to the environment (**Figure 21.20**). A major anatomical adaptation in mammals and birds is insulation, consisting of hair (often called fur), feathers, or fat layers. A thin coat of fur in the summer often becomes a thick, insulating coat during the winter. Also, most land mammals and birds react to cold by raising their fur or feathers; this adaptation traps a thicker layer of air next to the warm skin, improving the insulation. In people, our muscles raise our hair in the cold, causing goose bumps, a vestige from our furry ancestors. Aquatic mammals (such as seals) and aquatic birds (such as penguins) have a thick insulating layer of fat called blubber.

Some adaptations are physiological. In cold weather, hormonal changes tend to boost the metabolic rate of birds and mammals, increasing their heat production. Simply moving around more or shivering also produces heat as a metabolic by-product of the contraction of skeletal muscles. Honeybees survive cold winters by clustering together and shivering in their hive. Their metabolic activity generates enough heat to keep the cluster alive. Panting and sweating are examples of physiological adaptations that greatly increase cooling.

A variety of behavioral responses can regulate body temperature. Some birds and butterflies migrate seasonally to more suitable climates. Other animals, such as desert lizards, bask in the sun when it is cold and find cool, damp areas or burrows when it is hot. Honeybees cool their hive during hot weather by transporting water into it and fanning with their wings. Many animals cool themselves by bathing, and a few even spread saliva on their bodies. Some mammals, such as ground squirrels and chipmunks, drastically reduce their body temperature and metabolic rate by hibernating in burrows during the winter, thereby conserving energy. All of these mechanisms—anatomical, physiological, and behavioral—demonstrate how a single selection pressure (the need to thermoregulate) can drive the evolution of a multitude of adaptations in a wide variety of environments.

▼ Figure 21.20 **Methods of thermoregulation in animals.**

METHODS OF THERMOREGULATION		
Anatomical Adaptations (such as hair, fat, and feathers)	**Physiological Adaptations** (such as panting, shivering, and sweating)	**Behavioral Adaptations** (such as bathing, basking, hibernating, and migrating)



Campbell Essential Biology with Physiology, Fourth Edition, by Eric J. Simon, Jean L. Dickey, and Jane B. Reece. Published by Benjamin Cummings.

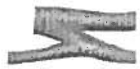
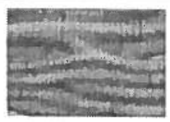
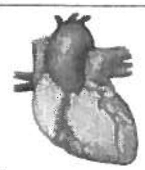
Chapter Review

SUMMARY OF KEY CONCEPTS

Go to **www.masteringbiology.com** for homework assignments, practice quizzes, Pearson eText, and more.

The Structural Organization of Animals

HIERARCHICAL ORGANIZATION OF ANIMALS

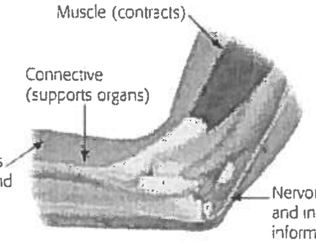
Level	Description	Example
Cell	The basic unit of all living organisms	 Muscle cell
Tissue	A collection of similar cells performing a specific function	 Cardiac muscle
Organ	Multiple tissues forming a structure that performs a specific function	 Heart
Organ system	A team of organs that work together	 Circulatory system
Organism	A living being, which depends on the coordination of all structural levels for homeostasis and survival	 Person

Form Fits Function

At every level, the structure of a body part is correlated with the task it must perform. Anatomy is the study of the structure of organisms, whereas physiology is the study of the function of an organism's structures.

Tissues

Animals have four main kinds of tissue.



Organs and Organ Systems

An organ is a collection of tissues that together perform a specific function; an organ system is a group of organs that together provide a vital function for the organism. Figure 21.8 summarizes the 11 major human organ systems.

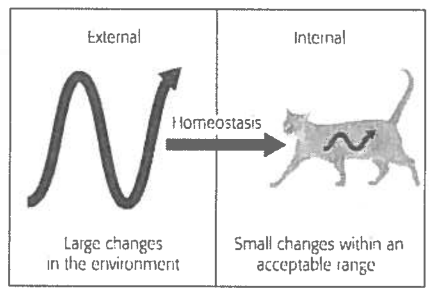
Exchanges with the External Environment

All animals are open systems, exchanging chemicals and energy with the environment. Every cell of a simple organism can exchange materials through direct contact with the environment. Large and complex body shapes require indirect exchange between extensively branched internal structures and the environment, usually via a circulatory system.

Regulating the Internal Environment

Homeostasis

Homeostasis is the body's tendency to maintain relatively constant internal conditions despite large fluctuations in the external environment.



Negative and Positive Feedback

In negative feedback, the most common homeostatic mechanism, the results of a process inhibit that process. Less common is positive feedback, in which the results of a process amplify that process.

Thermoregulation

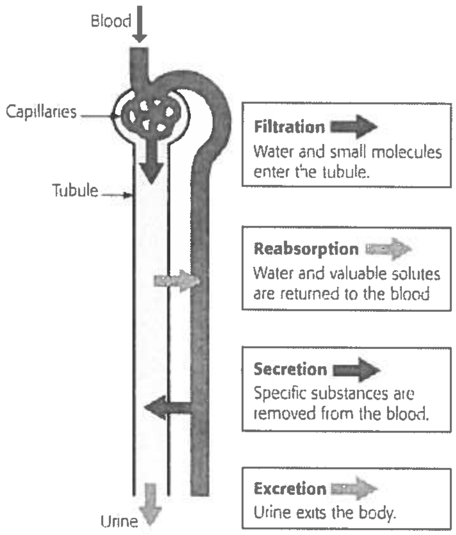
In thermoregulation, homeostatic mechanisms regulate internal body temperature. Endotherms are warmed primarily by heat generated during metabolism. Ectotherms are warmed primarily by heat absorbed from the environment.

Osmoregulation

All organisms balance the gain or loss of water and dissolved solutes. Osmoconformers do not tend to undergo a net gain or loss of water because their internal and external environments have similar solute concentrations. In contrast, osmoregulators must actively regulate their water balance—by drinking and urinating, for example.

Homeostasis in the Urinary System

The urinary system expels wastes and regulates solute and water balance. The following diagram summarizes the structure and function of the nephron, the functional unit of the kidney.



SELF-QUIZ

1. List as many units of structural hierarchy in your body as you can, in order from smallest to largest.
2. How might body shape affect whether an animal requires a circulatory system?
3. Which of the following best illustrates homeostasis?
   a. Most adult human beings are between 5 and 6 feet tall.
   b. The lungs and intestines have large surface areas for exchange.
   c. When the concentration of water in the blood goes up, the kidneys expel more water.
   d. When oxygen in the blood decreases, you may feel light-headed.
4. Most human cells are surrounded by an aqueous solution called ______________.
5. Stimulation of a nerve cell causes sodium ions to leak into the cell, and the sodium influx triggers the inward leaking of even more sodium. This is an example of ______________ feedback. An increase in the concentration of glucose in the blood stimulates the pancreas to secrete insulin, a hormone that lowers blood glucose concentrations. This is an example of ______________ feedback.
6. What is the main difference between endotherms and ectotherms?
7. Like most vertebrates, you are a(n) ______________; your body must actively regulate the gain or loss of water. In contrast, a lobster is a(n) ______________, living in an environment with a solute concentration similar to that of its body.
8. Which of the following is not one of the homeostatic functions of the kidney?
   a. reabsorption
   b. filtration
   c. excretion
   d. ingestion
9. Drinking alcohol makes you urinate more frequently because
   a. alcohol contains caffeine.
   b. alcohol inhibits the release of ADH, a hormone that increases water reabsorption in the kidneys.
   c. alcohol inhibits the release of ADH, a hormone that decreases water reabsorption in the kidneys.
   d. alcohol causes more water to filter from the blood into the kidneys.
10. What happens to most of the water that passes from the blood into the kidneys by filtration? What happens to the rest of it?

Answers to these questions can be found in Appendix: Self-Quiz Answers.

THE PROCESS OF SCIENCE

11. Eastern tent caterpillars (*Malacosoma americanum*) live in sizable groups in silk nests, or tents, typically in cherry and apple trees. They emerge early in the spring, when daily temperatures fluctuate from freezing to hot. Early in the morning, these black caterpillars rest in a tightly packed group on the east-facing surface of the tent. In midafternoon, the group is found on the tent undersurface, each caterpillar hanging from the tent by a few of its legs. Propose a hypothesis to explain this behavior. How could you test it?

BIOLOGY AND SOCIETY

12. The kidneys remove many drugs from the blood, and these substances show up in the urine. Some employers require a urine drug test at the time of hiring and/or at intervals during employment. Should an employee have the right to refuse a urine test? Should every job be subject to mandatory drug testing? If not, which jobs should be subject to testing? Would you take a drug test for a job? Why or why not?
13. Kidneys were the first organs to be successfully transplanted. A donor can live a normal life with a single kidney, making it possible for individuals to donate a kidney to an ailing relative or even an unrelated individual. Should a person be allowed to sell a kidney? Why or why not? What are some ethical issues raised by organ commerce?