Animal Form and Function

Review

Animals are complex systems of cells working in a coordinated fashion to monitor changing external conditions while maintaining a constant internal environment. To accomplish these tasks, animal cells are organized into systems that are specialized for particular functions. This section focuses on the structure of these various systems and how they accomplish particular tasks.

Cells are organized in the following ways:

1. **Tissues** are groups of similar cells performing a common function. Animal tissues are organized into four general categories:
   - **Epithelial** tissue (outer skin layers and internal protective coverings)
   - **Connective** tissue (bone, cartilage, blood)
   - **Nervous** tissue
   - **Muscle** tissue
2. An **organ** is a group of different kinds of tissues functioning together to perform a particular activity. For example, the heart consists of tissues from all four categories functioning together to pump blood through the body.
3. An **organ system** is two or more organs working together to accomplish a particular task. For example, the digestive system involves the coordinated activities of many organs, including the mouth, stomach, small and large intestines, pancreas, and liver.

The function of many animal systems is to contribute toward **homeostasis**, or the maintenance of stable, internal conditions within narrow limits. In many cases, stable conditions are maintained by **negative feedback**. In negative feedback, a sensing mechanism (a **receptor**) detects a change in conditions beyond specific limits. A control center, or **integrator** (often the brain), evaluates the change and activates a second mechanism (an **effector**) to correct the condition. Conditions are constantly monitored by receptors and evaluated by the control center. When the control center determines that conditions have returned to normal, corrective action is discontinued. Thus, in *negative* feedback, the original condition is canceled, or negated, so that conditions are returned to normal. Compare this with positive feedback, in which an action intensifies a condition so that it is driven further beyond normal limits. Such positive feedback is uncommon but does occur during childbirth (labor contractions), lactation (where milk production increases in response to an increase in nursing), and sexual orgasm.

Thermoregulation

Animals can be loosely grouped into two groups based upon how body temperature is maintained:

1. **Ectotherms** are animals that obtain body heat from their environment. Since their temperatures often vary with the temperature of their environment, they are sometimes referred to as **poikilotherms** ("changing temperature"). Examples include most invertebrates, amphibians, reptiles, and fish. Because many of these animals may feel cold to the touch they are called "cold-blooded" animals, but many land-dwelling ectotherms can exceed ambient temperatures by basking in the sun.
2. **Endotherms** are animals that generate their own body heat. They are also referred to as **homeotherms** because they maintain a constant internal temperature or as "warm-blooded" because their temperature is relatively warm compared to ectotherms.

Animals regulate their body temperatures by employing the following mechanisms:

1. **Cooling by evaporation.** Many animals lose heat by sweating. Since changing from a liquid to gaseous state requires energy (an endergonic reaction), body heat is removed when water vaporizes. Evaporative heat loss also occurs from the respiratory tract, a cooling process employed when animals pant.
2. **Warming by metabolism.** Muscle contraction and other metabolic activities generate heat. For example, shivering warms animals from the heat generated by muscle contractions.
3. **Adjusting surface area to regulate temperature.** The extremities of bodies (arms, hands, feet, ears) add considerable surface area to the body. By changing the volume of blood that flows to these areas by vasodilation or vasoconstriction (increasing or decreasing the diameter of blood vessels), heat can be lost or conserved. In hot environments, for example, elephants and jackrabbits *increase* blood flow to their large ears to reduce body temperature. In contrast, animals in cold environments *reduce* blood flow to their ears, hands, and feet to conserve heat. In addition, when blood moves through vessels toward an extremity, it flows adjacent to blood moving away from that extremity. In this example of **countercurrent exchange,** heat conduction from the warm blood to the returning cold blood is redirected to internal parts of the body before reaching the extremity.

In addition, all animals have various behavioral, physiological, or anatomical adaptations that increase their ability to survive in a particular environment. To survive cold temperatures, for example, some animals hibernate, while others have hair, feathers, or blubber. Some animals avoid heat by merely moving from sun to shade, while others restrict their activity to nights.

The Respiratory System

Animal cells require O_2 for aerobic respiration. If cells are not directly exposed to the outside environment, then some mechanism must provide gas exchange to internal cells, delivering O_2 and removing waste CO_2. The movement of gases into and out of the entire organism is called **respiration.** (This term, respiration, is also used to describe *cellular* respiration, the process of producing ATP within the mitochondria of cells.) The following gas exchange mechanisms are found in animals:

1. **Direct with environment.** Some animals are small enough to allow gas exchange directly with the outside environment. Many of these animals, such as the Platyhelminthes (flatworms), typically have large surface areas, and every cell either is exposed to the outside environment or is close enough that gases are available by diffusion through adjacent cells. In larger animals, such as the Annelida (segmented worms), gas exchange through the skin is augmented by a distribution system (a circulatory system) just inside the skin.
2. **Gills.** Gills are *evaginated* structures, or outgrowths from the body, that create a large surface area over which gas exchange occurs. Inside the gills, a circulatory system removes the oxygen and delivers waste CO_2. In some animals, such as polychaete worms (Annelida), the gills are *external* and unprotected. In other animals, the gills are *internal* and protected. In fish, for example, water enters the mouth, passes over the gills, and exits through the gill cover, or **operculum. Countercurrent exchange** between the opposing movements of water and the underlying blood through blood vessels maximizes the diffusion of O_2 into the blood and CO_2 into the water.
3. **Tracheae.** Insects have chitin-lined tubes, or **tracheae,** that permeate their bodies. Oxygen enters (or CO_2 exits) the tracheae through openings called **spiracles**; diffusion occurs across moistened tracheal endings.
4. **Lungs. Lungs** are *invaginated* structures, or cavities within the body of the animal. **Book lungs,** occurring in many spiders, are stacks of flattened membranes enclosed in an internal chamber.

Gas exchange in humans occurs as follows:

1. **Nose, pharynx, larynx.** Air enters the nose and passes through the nasal cavity, **pharynx,** and **larynx.** The larynx ("voice box") contains the vocal cords.
2. **Trachea.** After passing through the larynx, air enters the **trachea,** a cartilage-lined tube. When the animal is swallowing, a special flap called the **epiglottis** covers the trachea, preventing the entrance of solid and liquid material.
3. **Bronchi, bronchioles.** The trachea branches into two **bronchi** (singular, **bronchus**), which enter the lungs and then branch repeatedly, forming narrower tubes called **bronchioles.**

4. **Alveolus.** Each bronchiole branch ends in a small sac called an **alveolus** (plural, **alveoli**). Each alveolus is densely surrounded by blood-carrying capillaries.
5. **Diffusion between alveolar chambers and blood.** Gas exchange occurs by diffusion across the moist, sac membranes of the alveoli. Oxygen diffuses into the moisture covering the membrane, through the alveolar wall, through the blood capillary wall, into the blood, and into red blood cells. Carbon dioxide diffuses in the opposite direction.
6. **Bulk flow of O_2.** The circulatory system transports O_2 throughout the body within red blood cells. Red blood cells contain hemoglobin, iron-containing proteins to which O_2 bonds.
7. **Diffusion between blood and cells.** Blood capillaries permeate the body. Oxygen diffuses out of the red blood cells, across blood capillary walls, into interstitial fluids (the fluids surrounding the cells), and across cell membranes. Carbon dioxide diffuses in the opposite direction.
8. **Bulk flow of CO_2.** Most CO_2 is transported as dissolved bicarbonate ions (HCO_3^-) in the plasma, the liquid portion of the blood. The formation of HCO_3^-, however, occurs in the red blood cells, where the formation of carbonic acid (H_2CO_3) is catalyzed by the enzyme **carbonic anhydrase,** as follows:

$$CO_2 + H_2O \rightarrow H_2CO_3 \rightarrow H^+ + HCO_3^-$$

   Following their formation in the red blood cells, HCO_3^- ions diffuse back into the plasma. Some CO_2, however, does not become HCO_3^-; instead, it mixes directly with the plasma (as CO_2 gas) or binds with the amino groups of the hemoglobin molecules inside red blood cells.
9. **Bulk flow of air into and out of the lungs (mechanics of respiration).** Air is moved into and out of the lungs by changing their volume. The volume of the lungs is increased by the contraction of the **diaphragm** (a muscle under the lungs) and the **intercostal** muscles (muscles between the ribs). When the lung volume increases, the air pressure within the lungs decreases. This causes a pressure difference between the air in the lungs and the air outside the body. As a result, air rushes into the lungs by bulk flow. When the diaphragm and intercostal muscles relax, the volume of the lungs decreases, raising the pressure on the air, causing the air to rush out.
10. **Control of respiration.** Chemoreceptors in the carotid arteries (arteries that supply blood to the brain) monitor the pH of the blood. When a body is active, CO_2 production increases. When the CO_2 that enters the plasma is converted to HCO_3^- and H^+, the blood pH drops (becomes more acidic). In response, the chemoreceptors send nerve impulses to the diaphragm and intercostal muscles to increase respiratory rate. This results in a faster turnover in gas exchange, which, in turn, returns blood pH to normal. The regulation of the respiratory rate in this manner is an example of how homeostasis is maintained by negative feedback.

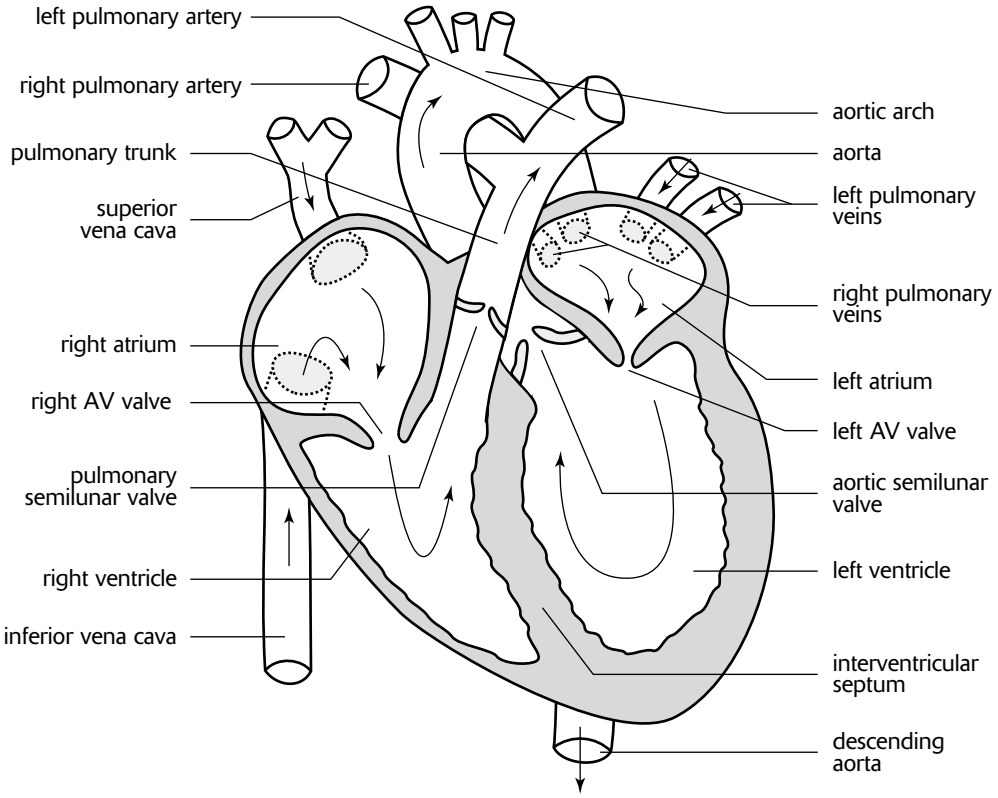
The Circulatory System

Large organisms require a transport system to distribute nutrients and oxygen and to remove wastes and CO_2 from cells distributed throughout the body. Two kinds of circulatory systems accomplish this internal transport.

1. **Open circulatory systems** pump blood into an internal cavity called a **hemocoel** (or cavities called **sinuses**), which bathe tissues with an oxygen- and nutrient-carrying fluid called **hemolymph.** The hemolymph returns to the pumping mechanism of the system, a **heart,** through holes called **ostia.** Open circulatory systems occur in insects and most mollusks.
2. In **closed circulatory systems,** the nutrient-, oxygen-, and waste-carrying fluid, **blood,** is *confined* to vessels. Closed circulatory systems are found among members of the phylum Annelida (earthworms, for example), certain mollusks (octopuses and squids), and vertebrates.

In the closed circulatory system of vertebrates, vessels moving *away* from the heart are called **arteries.** Arteries branch into smaller vessels, the **arterioles,** and then branch further into the smallest vessels, the **capillaries.** Gas and nutrient exchange occurs by diffusion across capillary walls into interstitial fluids and into surrounding cells. Wastes and excess interstitial fluids move in the opposite direction as they diffuse into the capillaries. The blood, now deoxygenated, remains in the capillaries and *returns* to the heart through **venules,** which merge to form larger **veins.** The heart then pumps the deoxygenated blood to the respiratory organ (gills or lungs) where arteries again branch into a capillary bed for gas exchange. The oxygenated blood then returns to the heart through veins. From here, the oxygenated blood is pumped, once again, throughout the body.

In the human heart, blood moves through the following structures, in the following order (Figure 12-1).



The Heart

Figure 12-1

1. **Right atrium.** *Deoxygenated* blood enters this chamber on the right side of the heart through two veins, the upper **superior vena cava** and the lower **inferior vena cava.** (Right and left refer to the right and left sides of the body.)
2. **Right ventricle.** Blood moves through the **right atrioventricular valve** (or **AV valve,** also called the **tricuspid valve**) and enters the **right ventricle.** The ventricles, with walls thicker and more muscular than those of the atria, contract and pump the blood into the **pulmonary artery,** through the **pulmonary semilunar valve,** and toward the lungs. When the ventricles *contract,* the AV valve closes and prevents blood moving backward into the atrium. When the ventricles *relax,* the semilunar valve prevents backflow from the pulmonary artery back into the ventricles.
3. **Left atrium.** After the lungs, the *oxygenated* blood returns to the left atrium through the **pulmonary veins.**
4. **Left ventricle.** Passing through the **left AV valve** (also called the mitral or bicuspid valve), the blood moves into the **left ventricle.** From here, the muscular left ventricle pumps the blood into the large artery, the **aorta,** through the **aortic semilunar valve,** and throughout the body. Similar to the valves on the right side of the heart, the left AV valve prevents movement of blood into the atrium, and the semilunar valve prevents backflow into the ventricle.

The blood pathway between the right side of the heart, to the lungs, and back to the left side of the heart is called the **pulmonary circuit.** The circulation pathway throughout the body (between the left and right sides of the heart) is the **systemic circuit.**

The **cardiac** or **heart cycle** refers to the rhythmic contraction and relaxation of heart muscles. The process is regulated by specialized tissues in the heart called **autorhythmic cells,** which are self-excitable and able to initiate contractions without external stimulation by nerve cells. The cycle occurs as follows:

1. The **SA (sinoatrial) node,** or **pacemaker,** located in the upper wall of the right atrium, spontaneously initiates the cycle by simultaneously contracting both atria and also by sending a delayed impulse that stimulates the **AV (atrioventricular) node.**
2. The **AV node** in the lower wall of the right atrium sends an impulse through the **bundle of His,** nodal tissue that passes down between both ventricles and then branches into the ventricles through the **Purkinje fibers.** This impulse results in the contraction of the ventricles.
3. When the ventricles contract (the **systole** phase), blood is forced through the pulmonary arteries and aorta. Also, the AV valves are forced to close. When the ventricles relax (the **diastole** phase), backflow into the ventricles causes the semilunar valves to close. The closing of AV valves, followed by the closing of the semilunar valves, produces the characteristic "lub-dup" sounds of the heart.

Hydrostatic pressure created by the heart forces blood to move through the arteries. As blood reaches the capillaries, however, blood pressure drops dramatically and approaches zero in the venules. Blood continues to move through the veins, *not because of the contractions of the heart,* but because of the movements of adjacent skeletal muscles which squeeze the blood vessels. Blood moves in the direction of the heart because valves in the veins prevent backflow.

Wastes and excess interstitial fluids enter the circulatory system when they diffuse into capillaries. However, not all of the interstitial fluids enter the capillaries. Instead, some interstitial fluids and wastes are returned to the circulatory system by way of the **lymphatic system,** a second network of capillaries and veins. The fluid in these lymphatic veins, called lymph, moves slowly through lymphatic vessels by the contraction of adjacent muscles. Valves in the lymphatic veins prevent backflow. Lymph returns to the blood circulatory system through two ducts located in the shoulder region. In addition to returning fluids to the circulatory system, the lymphatic system functions as a filter. **Lymph nodes,** enlarged bodies throughout the lymphatic system, act as cleaning filters and as immune response centers that defend against infection.

Blood contains the following:

1. **Red blood cells,** or **erythrocytes,** transport oxygen (attached to hemoglobin) and catalyze the conversion of CO_2 and H_2O to H_2CO_3. Mature red blood cells lack a nucleus, thereby maximizing hemoglobin content and thus their ability to transport O_2.
2. **White blood cells,** or **leukocytes,** consist of five major groups of disease-fighting cells that defend the body against infection.
3. **Platelets** are cell fragments that are involved in blood clotting. Platelets release factors that are involved in the conversion of the major clotting agent, **fibrinogen,** into its active form, **fibrin.** Threads of fibrin protein form a network that stops blood flow.
4. **Plasma** is the liquid portion of the blood that contains various dissolved substances.

The Excretory System

In general, excretory systems help maintain homeostasis in organisms by regulating water balance and by removing harmful substances.

Osmoregulation is the absorption and excretion of water and dissolved substances (solutes) so that proper water balance (and osmotic pressure) is maintained between the organism and its surroundings. Two examples follow:

1. **Marine fish.** The body of a marine fish is *hypo*osmotic with its environment — that is, it is less salty than the surrounding water. Thus, water is constantly lost by osmosis. In order to maintain their proper internal environment, marine fish constantly drink, rarely urinate, and secrete accumulated salts (that they acquire when they drink) out through their gills.
2. **Fresh water fish.** The body of a fresh water fish is *hyper*osmotic, or saltier than the surrounding water. Thus, water constantly diffuses into the fish. In response, fresh water fish rarely drink, constantly urinate, and absorb salts (that they lose in their urine) through their gills.

Various excretory mechanisms have evolved in animals for the purpose of osmoregulation and for the removal of toxic substances. Toxic substances include by-products of cellular metabolism, such as the nitrogen products of protein breakdown. Examples of important excretory mechanisms follow:

1. **Contractile vacuoles** are found in the cytoplasm of various protists, such as paramecia and amoebas. These vacuoles accumulate water, merge with the plasma membrane, and release the water to the environment.
2. **Flame cells (protonephridia)** are found in various Platyhelminthes, such as planaria. The flame cells are distributed along a branched tube system that permeates the flatworm. Body fluids are filtered across the flame cells, whose internal cilia move the fluids through the tube system. Wastes (water and salts) are excreted from the tube system through pores that exit the body.
3. **Nephridia** (or **metanephridia**) occur in pairs within each segment of most annelids, such as earthworms. Interstitial fluids enter a nephridium through a ciliated opening called a **nephrostome.** Fluids are concentrated as they pass through the **collecting tubule** due to selective secretion of materials into the surrounding coelomic fluid. Blood capillaries that surround the tubule reabsorb the secreted materials. At the end of the collecting tubule, the concentrated waste materials are excreted through an **excretory pore.** Nephridia exemplify a tube-type excretory system, where body fluids are selectively filtered as they pass through the tube. Materials to be retained are secreted back into the body fluids, while concentrated wastes continue through the tube to be excreted at the far end.
4. **Malpighian tubules** occur in many arthropods, such as terrestrial insects. Tubes attached to the midsection of the digestive tract of insects (midgut) collect body fluids from the hemolymph that bathe the cells. The fluids, which include both nitrogen wastes and materials to be retained (salts and water), are deposited into the midgut. As the fluids pass through the hindgut of the insect (along with digested food), materials to be retained pass back out though the walls of the digestive tract. Wastes continue in the tract and are excreted through the anus.
5. The vertebrate **kidney** consists of about a million individual filtering tubes called **nephrons.** Two kidneys produce waste fluids, or **urine,** which pass through **ureters** to the **bladder** for temporary storage. From the bladder, the urine is excreted through the **urethra** (Figure 12-2).

Individual nephrons in the human kidney consist of a tube and closely associated blood vessels (Figure 12-2). The nephron is strategically positioned in the kidney so that the tube winds from the outer portion of the kidney, the **cortex,** down through the **medulla,** then back up into the cortex, then back down through the medulla, draining into the center of the kidney, the **renal pelvis.** Details follow.

1. **Bowman's capsule.** The nephron tube begins with a bulb-shaped body at one end, the **Bowman's capsule.** A branch of the renal artery (the afferent arteriole) enters into the Bowman's capsule, branches to form a dense ball of capillaries called the **glomerulus,** and then exits the capsule (efferent arteriole).
2. **Convoluted tubule.** The **convoluted tubule** is a winding tube that begins with the **proximal convoluted tubule** at the Bowman's capsule and ends with the **distal convoluted tubule** where it joins with the **collecting duct.** The middle of the tubule, called the **loop of Henle,** is shaped like a hairpin and consists of a descending and ascending limb. Surrounding the tubule is a dense network of capillaries that originate from branches of the efferent arteriole that exited the glomerulus. These capillaries merge into the renal vein as they exit the nephron. The blood flow through the nephron, then, actually passes through two capillary beds, the glomerulus and the capillary network surrounding the tubule.
3. **Collecting duct.** The distal convoluted tube empties into the **collecting duct** which descends in the same direction as the descending limb toward the center of the kidney. A single collecting duct is shared by numerous nephrons and empties into the **renal pelvis,** which, in turn, drains into the ureter.

The operation of the human nephron consists of three processes, as follows:

1. **Filtration.** When blood enters the glomerulus, pressure forces water and solutes through the capillary walls into the Bowman's capsule. Solutes include glucose, salts, vitamins, nitrogen wastes, and any other substances small enough to pass through the capillary walls. Larger substances, such as red blood cells and proteins, remain in the capillaries. The material that enters the Bowman's capsule, or filtrate, flows into the convoluted tubule.
2. **Secretion.** As the filtrate passes through the proximal tubule and, later, through the distal tubule, additional material from the interstitial fluids joins the filtrate. This added material, which originates from the capillary network surrounding the nephron, is *selectively secreted* into the convoluted tubule by both passive and active transport mechanisms.

3. **Reabsorption.** As the filtrate moves *down* the loop of Henle, it becomes more *concentrated* due to passive flow of H_2O out of the tube. As the filtrate moves *up* the loop of Henle, it becomes more *dilute* due to passive and active transport of salts out of the tubule. At the end of the loop of Henle, then, the filtrate is *not* more concentrated. Rather, the *interstitial fluids* surrounding the nephron are *more* concentrated with salts. Next, the filtrate descends through the collecting duct toward the renal pelvis. As it passes through the salts concentrated in the interstitial fluids, water passively moves out of the collecting duct and into the interstitial fluids. When the filtrate drains into the renal pelvis, it is concentrated urine.

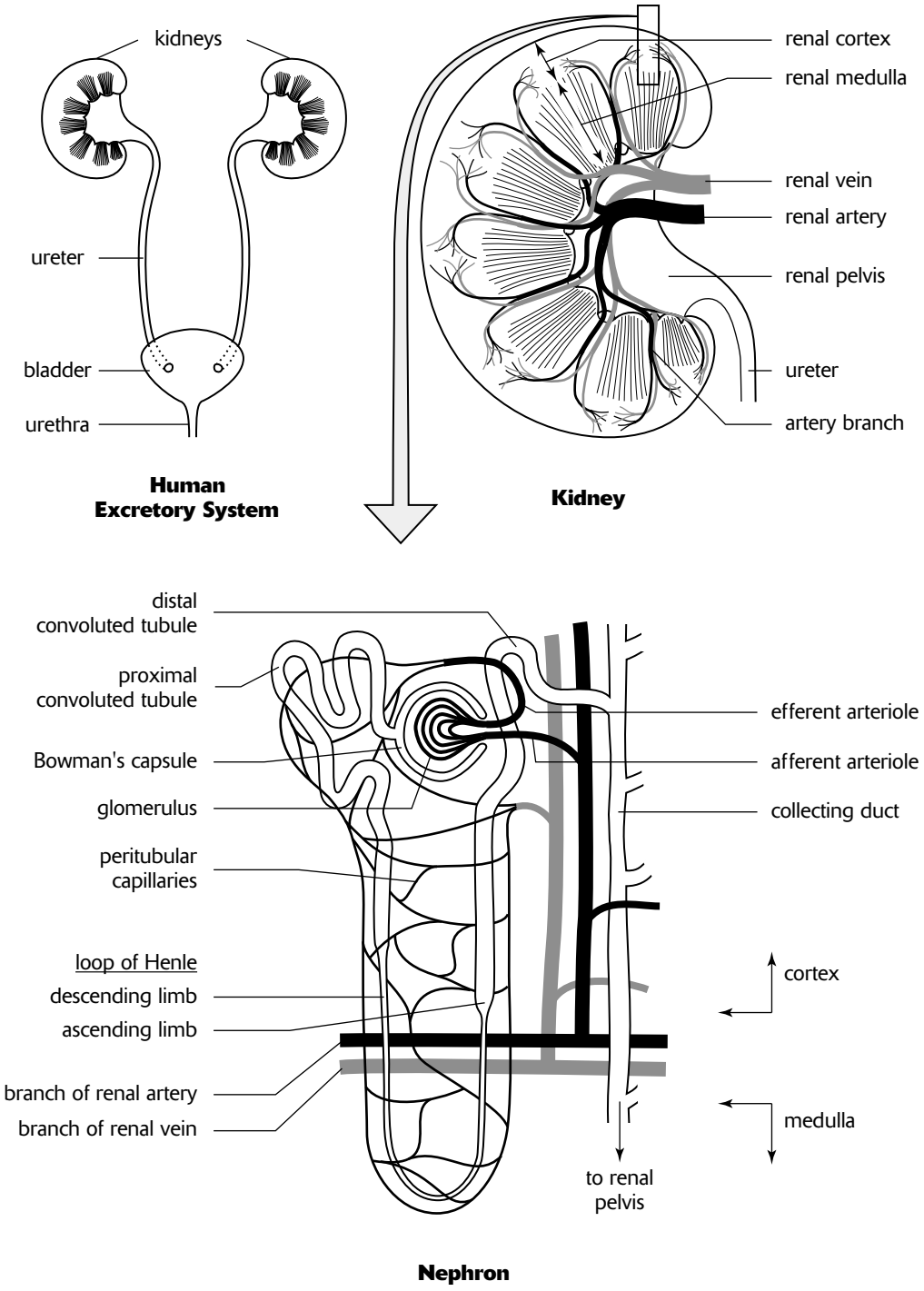


Figure 12-2

Two hormones influence osmoregulation by regulating the concentration of salts in the urine, as follows:

1. **Antidiuretic hormone** (**ADH**) increases the reabsorption of water by the body and increases the concentration of salts in the urine. It does this by increasing the permeability of the *collecting duct to water.* As a result, urine becomes more concentrated as water diffuses out of the collecting duct as the filtrate descends into the renal pelvis.
2. **Aldosterone** increases both the reabsorption of water and the reabsorption of Na^+. It does this by increasing the permeability of the *distal convoluted tubule and collecting duct to* Na^+. As a result, more Na^+ diffuses out of this tubule and duct. Since the Na^+ increases the salt concentration outside the tubule, water passively follows.

Nitrogen forms a major waste product in animals. When amino acids and nucleic acids are broken down, they release toxic ammonia (NH_3). To rid the body of this toxin, several mechanisms have evolved, each appropriate to the habitat or survival of the animal.

1. Aquatic animals excrete NH_3 (or NH_4^+) directly into the surrounding water.
2. Mammals convert NH_3 to **urea** in their livers. Urea is significantly less toxic than NH_3 and thus requires less water to excrete in the urine.
3. Birds, insects, and many reptiles convert urea to **uric acid.** Since uric acid is mostly insoluble in water, it precipitates and forms a solid. This allows considerable water conservation by permitting the excretion of nitrogen waste as a solid. In birds, the precipitation also allows the nitrogen wastes to be securely isolated in a special sac in the egg (the **allantois**), apart from the vulnerable developing embryo.

The Digestive System

Digestion is the chemical breakdown of food into smaller molecules. In an individual cell, digestion is accomplished by **intracellular** digestion when a lysosome containing digestive enzymes merges with a food vacuole. In most animals, however, the food ingested is too large to be engulfed by individual cells. Thus, food is first digested in a **gastrovascular cavity** by **extracellular** digestion and then absorbed by individual cells.

During digestion, four different groups of molecules are commonly encountered. Each is broken down into its molecular components by specific enzymes, as follows:

1. **Starches** are broken down into glucose molecules.
2. **Proteins** are broken down into amino acids.
3. **Fats** (or **lipids**) are broken down into glycerol and fatty acids.
4. **Nucleic acids** are broken down into nucleotides.

In humans and other mammals, digestion follows the following sequence of events. In particular, note which kinds of molecules are digested (broken down) and by which enzymes. Since enzymes are specific for different bonds, only a representative few of the numerous enzymes are given.

1. **Mouth. Salivary amylase,** secreted into the mouth by the salivary glands, begins the breakdown of *starch* into maltose (a disaccharide). Chewing reduces the size of food particles, thereby increasing the surface area upon which amylase and subsequent enzymes can operate. Food is shaped into a ball, or **bolus,** and then swallowed.
2. **Pharynx.** When food is swallowed and passed into the throat, or **pharynx,** a flap of tissue, the **epiglottis,** blocks the trachea so that solid and liquid material enter only the esophagus.
3. **Esophagus.** Food moves through the esophagus, a tube leading to the stomach, by muscular contractions called **peristalsis.**
4. **Stomach.** The stomach secretes **gastric juice,** a mixture of digestive enzymes and hydrochloric acid (HCl), and serves a variety of functions, as follows:
   - *Storage.* Because of its accordionlike folds, the wall of the stomach can expand to store two to four liters of material.
   - *Mixing.* The stomach mixes the food with water and gastric juice to produce a creamy medium called **chyme.**

- *Physical breakdown.* Muscles churn the contents of the stomach, *physically* breaking food down into smaller particles. In addition, HCl from the gastric juice denatures (or unfolds) proteins and loosens the cementing substances between cells of the food. Also, the HCl kills most bacteria that may accompany the food.
- *Chemical breakdown. Proteins* are *chemically* broken down (digested) by the enzyme **pepsin.** Stomach cells producing pepsin are protected from self-digestion because they produce and secrete an inactive form, **pepsinogen.** Pepsinogen is activated into pepsin by HCl, which is produced by other stomach cells. Thus, only after pepsinogen is secreted into the stomach cavity can protein digestion begin. Once protein digestion begins, the stomach is protected by a layer of mucus secreted by still other cells in the stomach lining. Failure of the mucus to protect the stomach can lead to lesions, or **peptic ulcers.** Long believed to be caused by stress, diet, or other factors, most ulcers are now known to be caused by bacteria and can be successfully treated with antibiotics.
- *Controlled release.* Movement of chyme into the small intestine is regulated by a valve at the end of the stomach, the **pyloric sphincter.**

5. **Small intestine.** The first twenty-five cm of the small intestine, the **duodenum,** continues the digestion of *starches* and *proteins* (which began in the mouth and stomach, respectively) as well as all remaining food types (including *fats* and *nucleotides*). Enzymes for these various processes originate from the following sources:
   - **Small intestine.** The wall of the **small intestine** is the source of various enzymes, including **proteolytic** enzymes (or **proteases,** enzymes that digest proteins, such as **aminopeptidase**), maltase and lactase (for the digestion of disaccharides), and **phosphatases** (for the digestion of nucleotides).
   - **Pancreas.** The pancreas produces various enzymes, including **trypsin** and **chymotrypsin** (proteases), **lipase** (digestion of fats), and **pancreatic amylase** (digestion of starch). These and other enzymes, packaged in an alkaline solution that serves to neutralize the HCl in the chyme, enter the duodenum through the pancreatic duct.
   - **Liver.** The liver produces bile, which functions to *emulsify* fats. Emulsification is the breaking up of fat globules into smaller fat droplets, increasing the surface area upon which fat-digesting enzymes (lipase, for example) can operate. Since bile does not chemically change anything, it is not an enzyme. Bile is also alkaline, serving to help neutralize the HCl in the chyme. The bile is stored adjacent to the liver in the **gallbladder** and flows through the bile duct where it merges with the pancreatic duct.
   - The remainder of the small intestine (nearly six meters) absorbs the breakdown products of food. It is characterized by **villi** and **microvilli,** fingerlike projections of the intestinal wall that increase its total absorptive surface area. Amino acids and sugars are absorbed into blood capillaries, while most of the fatty acids and glycerol are absorbed into the lymphatic system.
6. **Large intestine.** The main function of the large intestine, or colon, is the reabsorption of water to form solid waste, or **feces.** Feces are stored at the end of the large intestine, in the **rectum,** and excreted through the **anus.** Various harmless bacteria live in the large intestine, including some that produce vitamin K, which is absorbed through the intestinal wall. At the beginning of the large intestine, there is a short branch to a dead-end pouch which bears a fingerlike projection called the appendix. Other than a possible role in the immune response, the appendix is significant only when it becomes inflamed, causing appendicitis. In herbivores, the dead-end pouch is much enlarged and is called the **cecum.** It harbors bacteria that help in the digestion of cellulose.

Hormones are involved in the digestive process. Three important hormones are described below:

1. **Gastrin** is produced by cells in the stomach lining when food reaches the stomach or when the nervous system, through smell or sight, senses the availability of food. Gastrin enters the blood stream and stimulates other cells of the stomach to produce gastric juices.
2. **Secretin** is produced by the cells lining the duodenum when food enters. Secretin stimulates the pancreas to produce bicarbonate which, when deposited into the small intestine, neutralizes the acidity of the chyme.
3. **Cholecystokinin** is produced by the small intestine in response to the presence of fats. Cholecystokinin stimulates the gallbladder to release bile and the pancreas to release its enzymes.

The Nervous System

The basic structural unit of the nervous system is a nerve cell, or **neuron.** It consists of the following parts:

1. The **cell body** contains the nucleus and other cellular organelles.
2. The **dendrite** is typically a short, abundantly branched, slender extension of the cell body that *receives* stimuli.
3. The **axon** is typically a long, slender extension of the cell body that *sends* nerve impulses.

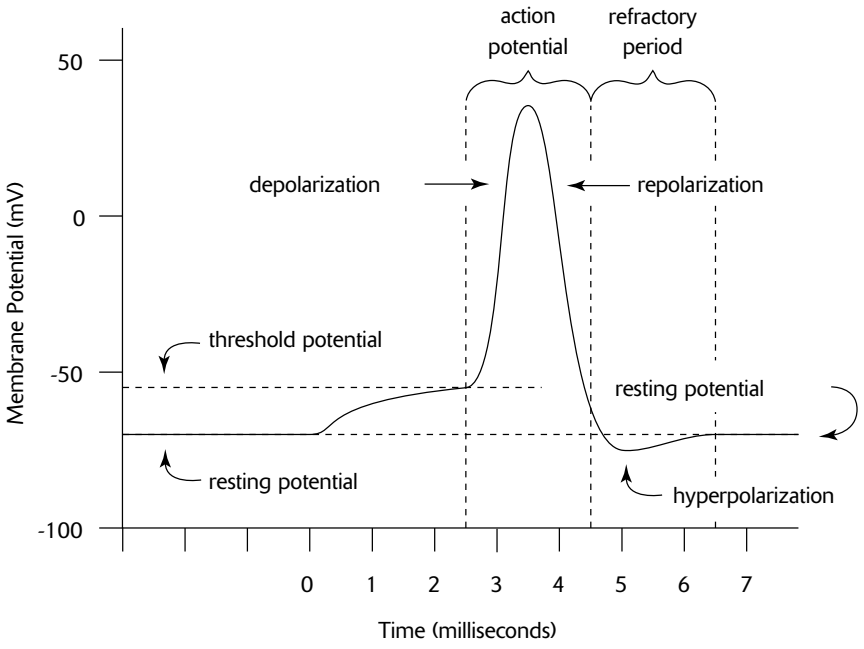
A nerve impulse begins at the tips of the dendrite branches, passes through the dendrites to the cell body, then through the axon, and finally terminates at branches of the axon.

Neurons can be classified into three general groups by their functions:

1. **Sensory neurons** (or **afferent neurons**) receive the initial stimulus. For example, sensory neurons embedded in the retina of the eye are stimulated by light, while certain sensory neurons in the hand are stimulated by touch.
2. **Motor neurons** (or **efferent neurons**) stimulate **effectors,** target cells that produce some kind of response. For example, efferent neurons may stimulate muscles (creating a movement to maintain balance or to avoid pain, for example), sweat glands (to cool the body), or cells in the stomach (to secrete gastrin in response to the smell of food, perhaps).
3. **Association neurons** (or **interneuron neurons**) are located in the spinal cord or brain and receive impulses from sensory neurons or send impulses to motor neurons. Interneurons are **integrators,** evaluating impulses for appropriate responses.

The transmission of a nerve impulse along a neuron from one end to the other occurs as a result of chemical changes across the membrane of the neuron. The membrane of an unstimulated neuron is **polarized,** that is, there is a difference in electrical charge between the outside and inside of the membrane. In particular, the *inside is negative* with respect to the outside. Polarization is established by maintaining an excess of sodium ions ($\mathbf{Na^+}$) on the outside and an excess of potassium ions ($\mathbf{K^+}$) on the inside. A certain amount of Na^+ and K^+ is always leaking across the membrane, but Na^+/K^+ pumps in the membrane actively restore the ions to the appropriate side. Other ions, such as large, negatively charged proteins and nucleic acids, reside inside the cell. *It is these large, negatively charged ions that contribute to the overall negative charge on the inside of the cell membrane* compared to the outside.

The following events characterize the transmission of a nerve impulse (Figure 12-3).



Action Potential in a Neuron

Figure 12-3

1. **Resting potential.** The resting potential describes the unstimulated, polarized state of a neuron (at about –70 millivolts).
2. **Action potential.** In response to a stimulus, **gated ion channels** in the membrane suddenly open and permit the *Na^+ on the outside to rush into the cell.* As the positively charged Na^+ rush in, the charge on the cell membrane becomes **depolarized,** or more positive on the inside (from –70 toward 0 millivolts). If the stimulus is strong enough—that is, if it is above a certain **threshold level**—more Na^+ gates open, increasing the inflow of Na^+ even more, causing an **action potential,** or complete depolarization (about +30 millivolts). This, in turn, stimulates neighboring Na^+ gates, further down the neuron, to open. In this manner, the action potential travels down the length of the neuron as opened Na^+ gates stimulate neighboring Na^+ gates to open. The action potential is an **all-or-nothing event:** when the stimulus fails to produce a depolarization that exceeds the threshold value, no action potential results, but when threshold potential is exceeded, complete depolarization occurs.
3. **Repolarization.** In response to the inflow of Na^+, another kind of gated channel opens, this time allowing the *K^+ on the inside to rush out of the cell.* The movement of K^+ out of the cell causes **repolarization** by restoring the original membrane polarization. Unlike the resting potential, however, the K^+ are on the outside and the Na^+ are on the inside. Soon after the K^+ gates open, the Na^+ gates close.
4. **Hyperpolarization.** By the time the K^+ gated channels close, more K^+ have moved out of the cell than is actually necessary to establish the original polarized potential. Thus, the membrane becomes **hyperpolarized** (about –80 millivolts).
5. **Refractory period.** With the passage of the action potential, the cell membrane is in an unusual state of affairs. The membrane is polarized, but the Na^+ and K^+ are on the wrong sides of the membrane. During this **refractory period,** the neuron will not respond to a new stimulus. To reestablish the original distribution of these ions, the Na^+ and K^+ are returned to their resting potential location by Na^+/K^+ pumps in the cell membrane. Once these ions are completely returned to their resting potential location, the neuron is ready for another stimulus.

Some neurons possess a **myelin sheath,** which consists of a series of **Schwann cells** that encircle the axon. The Schwann cells act as insulators and are separated by gaps of unsheathed axon called **nodes of Ranvier.** Instead of traveling continuously down the axon, the action potential jumps from node to node (**saltatory conduction**), thereby speeding the propagation of the impulse.

A **synapse,** or **synaptic cleft,** is the gap that separates adjacent neurons. Transmission of an impulse across a synapse, from **presynaptic cell** to **postsynaptic cell,** may be electrical or chemical. In electrical synapses, the action potential travels along the membranes of **gap junctions,** small tubes of cytoplasm that connect adjacent cells. In most animals, however, most synaptic clefts are traversed by chemicals, as follows:

1. **Calcium (Ca^{2+}) gates open.** When an action potential reaches the end of an axon, the depolarization of the membrane causes gated channels to open and allow Ca^{2+} to enter the cell.
2. **Synaptic vesicles release neurotransmitter.** The influx of Ca^{2+} into the terminal end of the axon causes **synaptic vesicles** to merge with the presynaptic membrane, releasing molecules of a chemical called a **neurotransmitter** into the synaptic cleft.
3. **Neurotransmitter binds with postsynaptic receptors.** The neurotransmitter diffuses across the synaptic cleft and binds with proteins on the postsynaptic membrane. Different proteins are receptors for different neurotransmitters.
4. **The postsynaptic membrane is excited or inhibited.** Depending upon the kind of neurotransmitter and the kind of membrane receptors, there are two possible outcomes for the postsynaptic membrane.
   - *If Na^+ gates open,* the membrane becomes depolarized and results in an **excitatory postsynaptic potential** (**EPSP**). If the threshold potential is exceeded, an action potential is generated.
   - *If K^+ gates open,* the membrane becomes more polarized (hyperpolarized) and results in an **inhibitory postsynaptic potential** (**IPSP**). As a result, it becomes more difficult to generate an action potential on this membrane.
5. **The neurotransmitter is degraded and recycled.** After the neurotransmitter binds to the postsynaptic membrane receptors, it is broken down by enzymes in the synaptic cleft. For example, a common neurotransmitter, **acetylcholine,** is broken down by **cholinesterase.** Degraded neurotransmitters are recycled by the presynaptic cell.

Some of the common neurotransmitters and the kind of activity they generate are summarized below:

1. **Acetylcholine** is commonly secreted at **neuromuscular junctions,** the gaps between motor neurons and muscle cells, where it stimulates muscles to contract. At other kinds of junctions, it typically produces an inhibitory post-synaptic potential.
2. **Epinephrine, norepinephrine, dopamine,** and **serotonin** are derived from amino acids and are mostly secreted between neurons of the central nervous system.
3. **Gamma aminobutyric acid** (**GABA**) is usually an inhibitory neurotransmitter among neurons in the brain.

The nervous systems of humans and other vertebrates consist of two parts, as follows:

1. The **central nervous system** (CNS) consists of the brain and spinal cord.
2. The **peripheral nervous system** consists of sensory neurons that transmit impulses *to the CNS* and motor neurons that transmit impulses *from the CNS* to effectors. The motor neuron system can be divided into two groups, as follows:
   - The **somatic nervous system** directs the contraction of skeletal muscles.
   - The **autonomic nervous system** controls the activities of organs and various involuntary muscles, such as cardiac and smooth muscles.

There are two divisions of the autonomic nervous system:

1. The **sympathetic nervous system** is involved in the stimulation of activities that prepare the body for action, such as increasing the heart rate, increasing the release of sugar from the liver into the blood, and other activities generally considered as fight-or-flight responses (responses that serve to fight off or retreat from danger).
2. The **parasympathetic nervous system** activates tranquil functions, such as stimulating the secretion of saliva or digestive enzymes into the stomach.

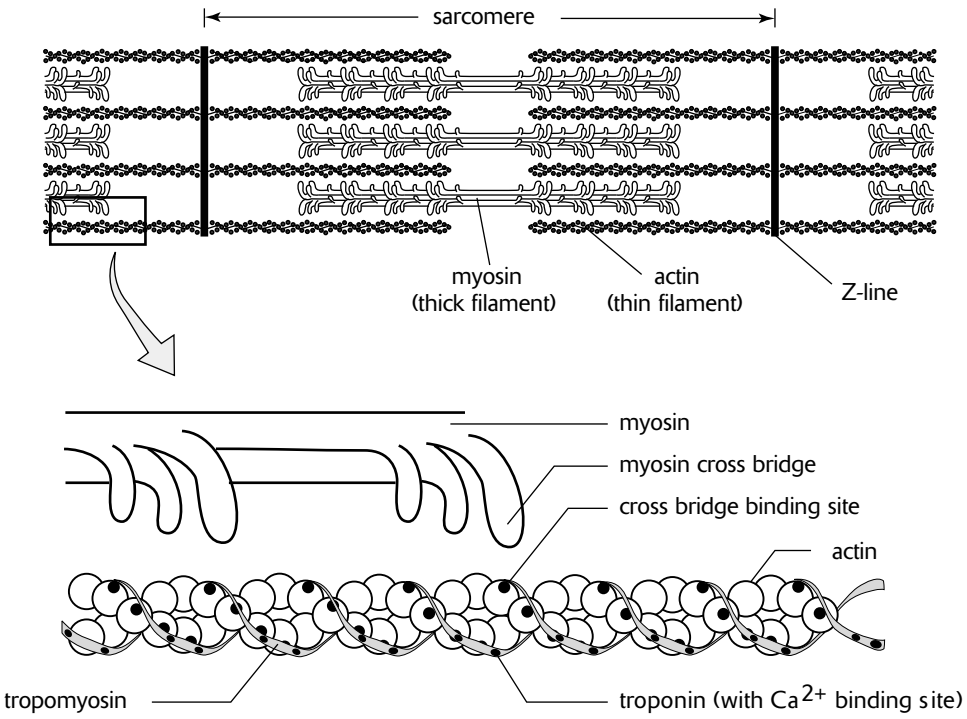
Generally, both sympathetic and parasympathetic systems target the same organs but often work antagonistically. For example, the sympathetic system accelerates the cardiac cycle, while the parasympathetic slows it down. Each system is stimulated as is appropriate to maintain homeostasis.

A **reflex arc** is a rapid, involuntary response to a stimulus. It consists of two or three neurons—a sensory and motor neuron and, in some reflex arcs, an interneuron. Although neurons may transmit information about the reflex response to the brain, the brain does not actually integrate the sensory and motor activities.

The Muscular System

A skeletal muscle consists of numerous muscle cells called **muscle fibers.** Muscle fibers have special terminology and distinguishing characteristics, as follows:

1. The **sarcolemma,** or plasma membrane of the muscle cell, is highly invaginated by **transverse tubules** (or **T tubules**) that permeate the cell.
2. The **sarcoplasm,** or cytoplasm of the muscle cell, contains calcium-storing **sarcoplasmic reticulum,** the specialized endoplasmic reticulum of a muscle cell.
3. Skeletal muscle cells are *multinucleate*. The nuclei lie along the periphery of the cell, forming swellings visible through the sarcolemma.
4. Nearly the entire volume of the muscle cell is filled with numerous, long **myofibrils.** Myofibrils consist of two types of filaments, as follows (Figure 12-4):
   - *Thin* filaments consist of two strands of the globular protein **actin** arranged in a double helix. Along the length of the helix are **troponin** and **tropomyosin** molecules that cover special binding sites on the actin.
   - *Thick* filaments consist of groups of the filamentous protein **myosin.** Each myosin filament forms a protruding head at one end. An array of myosin filaments possesses protruding heads at numerous positions at both ends.



Sliding-Filament Model of Muscle Contraction

Figure 12-4

Within a myofibril, actin and myosin filaments are parallel and arranged side by side. The overlapping filaments produce a repeating pattern that gives skeletal muscle a striated appearance. Each repeating unit of the pattern, called a sarcomere, is separated by a border, or **Z-line,** to which the actin filaments are attached. The myosin filaments, with their protruding heads, are located between the actin, unattached to the Z-line.

Muscle contraction is described by the **sliding-filament model,** as follows:

1. **ATP binds to a myosin head and forms ADP + P_i.** When ATP binds to a myosin head, it is converted to ADP and P_i, which remain attached to the myosin head.
2. **Ca^{2+} exposes the binding sites on the actin filaments.** Ca^{2+} binds to the troponin molecule causing tropomyosin to expose positions on the actin filament for the attachment of myosin heads.
3. **Cross bridges between myosin heads and actin filaments form.** When attachment sites on the actin are exposed, the myosin heads bind to actin to form cross bridges.
4. **ADP and P_i are released and sliding motion of actin results.** The attachment of cross bridges between myosin and actin causes the release of ADP and P_i. This, in turn, causes a change in shape of the myosin head, which generates a sliding movement of the actin toward the center of the sarcomere. This pulls the two Z-lines together, effectively contracting the muscle fiber.
5. **ATP causes the cross bridges to unbind.** When a new ATP molecule attaches to the myosin head, the cross bridge between the actin and myosin breaks, returning the myosin head to its unattached position.

Without the addition of a new ATP molecule, the cross bridges remain attached to the actin filaments. This is why corpses are stiff (new ATP molecules are unavailable).

Neurons form specialized synapses with muscles called **neuromuscular junctions.** Muscle contraction is stimulated through the following steps:

1. **Action potential generates release of acetylcholine.** When an action potential of a neuron reaches the neuromuscular junction, the neuron secretes the neurotransmitter acetylcholine, which diffuses across the synaptic cleft.
2. **Action potential is generated on sarcolemma and throughout the T-tubules.** Receptors on the sarcolemma initiate a depolarization event and action potential. The action potential travels along the sarcolemma throughout the transverse system of tubules.
3. **Sarcoplasmic reticulum releases Ca^{2+}.** As a result of the action potential throughout the transverse system of tubules, the sarcoplasmic reticulum releases Ca^{2+}.
4. **Myosin cross bridges form.** The Ca^{2+} released by the sarcoplasmic reticulum binds to troponin molecules on the actin helix, prompting tropomyosin molecules to expose binding sites for myosin cross-bridge formation. If ATP is available, muscle contraction begins.

Humans and other vertebrates have three kinds of muscles:

1. **Skeletal muscle** is attached to bones and causes movements of the body.
2. **Smooth muscle** lines the walls of blood vessels and the digestive tract where it serves to advance the movement of substances. Due to its arrangement of actin and myosin filaments, smooth muscle does not have the striated appearance of skeletal muscle. In addition, the sarcolemma does not form a system of transverse tubules, and as a result, contraction is controlled and relatively slow, properties appropriate for its function.
3. **Cardiac muscle** is responsible for the rhythmic contractions of the heart. Although striated, cardiac muscle differs from skeletal muscle in that it is highly branched with cells connected by gap junctions. In addition, cardiac muscle generates its own action potential, which spreads rapidly throughout muscle tissue by electrical synapses across the gap junctions.

The Immune System

The internal environment of animals provides attractive conditions for the growth of bacteria, viruses, and other organisms. Although some of these organisms can live symbiotically within animals, many either cause destruction of cells or produce toxic chemicals. To protect against these foreign invaders, humans possess three levels of defense.

The **skin** and **mucous membranes** provide a *nonspecific first line of defense* against invaders entering through the skin or through openings into the body. A nonspecific defense is not specialized for a particular invader. Rather, it is a general defense against all kinds of pathogens. The first line of defense features the following characteristics:

1. **Skin** is a physical and hostile barrier covered with oily and acidic (pH from 3 to 5) secretions from sweat glands.
2. **Antimicrobial proteins** (such as **lysozyme,** which breaks down the cell walls of bacteria) are contained in saliva, tears, and other secretions found on mucous membranes.
3. **Cilia** that line the lungs serve to sweep invaders out of the lungs.
4. **Gastric juice** of the stomach kills most microbes.
5. **Symbiotic bacteria** found in the digestive tract and the vagina outcompete many other organisms that could cause damage.

The *second line of defense* involves several nonspecific mechanisms, as follows:

1. **Phagocytes** are white blood cells (leukocytes) that engulf pathogens by phagocytosis. They include **neutrophils** and **monocytes.** Monocytes enlarge into large phagocytic cells called **macrophages.** Other white blood cells called **natural killer cells** (**NK cells**) attack abnormal body cells (such as tumors) or pathogen-infected body cells.
2. **Complement** is a group of about twenty proteins that "complement" defense reactions. These proteins help attract phagocytes to foreign cells and help destroy foreign cells by promoting cell lysis (breaking open the cell).
3. **Interferons** are substances secreted by cells invaded by viruses that stimulate neighboring cells to produce proteins that help them defend against the viruses.

4. The **inflammatory response** is a series of nonspecific events that occur in response to pathogens. When skin is damaged, for example, and bacteria or other organisms enter the body, the following events occur:
   - **Histamine** is secreted by **basophils,** white blood cells found in connective tissue.
   - **Vasodilation** (dilation of blood vessels), stimulated by histamine, increases blood supply to the damaged area and allows for easier movement of white blood cells (and other body fluids) through blood vessel walls. This also causes redness, an increase in temperature, and swelling. The increase in temperature, like a fever, may stimulate white blood cells, and they may make the environment inhospitable to pathogens.
   - **Phagocytes,** attracted to the injury by chemical gradients of complement, arrive and engulf pathogens and damaged cells.
   - **Complement** helps phagocytes engulf foreign cells, stimulate basophils to release histamine, and help lyse foreign cells.

The **immune response** is the *third line of defense*. It differs from the inflammatory response in that it targets *specific* **antigens.** An antigen is any molecule, usually a protein or polysaccharide, that can be identified as foreign. It may be a toxin (injected into the blood by the sting of an insect, for example), a part of the protein coat of a virus, or a molecule unique to the plasma membranes of bacteria, protozoa, pollen, or other foreign cells.

The **major histocompatibility complex,** or **MHC,** is the mechanism by which the immune system is able to differentiate between self and nonself cells. The MHC is a collection of glycoproteins (proteins with a carbohydrate) that exists on the membranes of all body cells. The proteins of a single individual are unique, originating from twenty genes, each with more than fifty alleles each. Thus, it is extremely unlikely that two people, except for identical twins, will possess cells with the same set of MHC molecules.

The primary agents of the immune response are **lymphocytes,** white blood cells (leukocytes) that originate in the bone marrow (like all blood cells) but concentrate in lymphatic tissues such as the lymph nodes, the thymus gland, and the spleen. The various kinds of lymphocytes are grouped as follows:

1. **B cells.** These are lymphocytes that originate *and* mature in the *bone marrow* (remember B cell for bone). B cells respond to *antigens*. The plasma membrane surface of B cells is characterized by specialized **antigen receptors** called **antibodies.** Antibodies have the following properties:
   - Antibodies are proteins.
   - Each antibody is specific to a particular antigen.
   - There are five classes of antibodies (or **immunoglobulins**): IgA, IgD, IgE, IgG, IgM. Each class is associated with a particular activity.
   - Each class of antibodies is a variation of a basic Y-shaped protein that consists of constant regions and variable regions. The variable regions are sequences of amino acids that differ among antibodies and give them specificity to antigens.
   - Antibodies inactivate antigens by binding to them. Inactivation is followed by macrophage phagocytosis. In addition, by binding to surface antigens of nonself cells, antibodies stimulate complement proteins to bring about the lysis of pathogens.

   When B cells encounter antigens that specifically bind to their antibodies, the B cells proliferate, producing two kinds of daughter B cells, as follows:

   - **Plasma cells** are B cells that release their specific antibodies which then circulate through the body, binding to antigens.
   - **Memory cells** are long-lived B cells that do not release their antibodies in response to the immediate antigen invasion. Instead, the memory cells circulate in the body and respond quickly to eliminate any *subsequent* invasion by the same antigen. This mechanism provides immunity to many diseases after the first occurrence of the disease.
2. **T cells.** T cells are lymphocytes that originate in the bone marrow, but mature in the *thymus gland* (T cell for thymus). Like B cells, the plasma membranes of T cells have antigen receptors. However, these receptors are not antibodies, but recognition sites for *molecules displayed by nonself cells.* Self and nonself cells are distinguished as follows:

- The MHC markers on the plasma membrane of cells distinguish between self and nonself cells.
- When a body cell is invaded by a virus, by a foreign cell, or by any antigen, the body cell displays a combination of self and nonself markers. T cells interpret this aberrant display of markers as nonself.
- Cancer cells or tissue transplant cells, or other cells that display aberrant markers, are recognized as nonself cells by T cells.

When T cells encounter nonself cells, they divide and produce two kinds of cells, as follows:

- **Cytotoxic T cells** (or **killer T cells**) recognize and destroy nonself cells by puncturing them, thus causing them to lyse.
- **Helper T cells** stimulate the proliferation of B cells and cytotoxic T cells.

When an antigen binds to a B cell or when a nonself cell binds to a T cell, the B cell or T cell begins to divide, producing numerous daughter cells, all identical copies of the parent cell. This process is called **clonal selection,** since only the B or T cell that bears the effective antigen receptor is "selected" and reproduces to make clones, or identical copies of itself. Clonal selection results in a proliferation of B cells and T cells that will engage a specific, invading antigen.

The responses of the immune system are categorized into two kinds of reactions, as follows:

1. The **cell-mediated response** uses mostly *T cells* and responds to *any nonself cell, including cells invaded by pathogens.* When a nonself cell binds to a T cell, the T cell undergoes clonal selection, initiating the following chain of events.
   - **T cells produce cytotoxic T cells.** These cells destroy nonself cells.
   - **T cells produce helper T cells.**
   - **Helper T cells bind to macrophages.** Macrophages that have engulfed pathogens display aberrant plasma membrane markers. Helper T cells identify these marker combinations as nonself and bind to these macrophages.
   - **Helper T cells produce interleukins to stimulate a proliferation of T cells and B cells.** When helper T cells bind with macrophages, they release *interleukins,* or communication chemicals "between leukocytes." The interleukins initiate a sequence of positive-feedback events that result in the proliferation of interleukins, macrophages, helper T cells, B cells, and cytotoxic T cells.
2. The **humoral response** (or **antibody-mediated response**) involves most cells and responds to *antigens or pathogens that are circulating in the lymph or blood* ("humor" is a medieval term for body fluid). It includes the following events:
   - **B cells produce plasma cells.** The plasma cells, in turn, release antibodies that bind with antigens or antigen-bearing pathogens.
   - **B cells produce memory cells.** Memory cells provide future immunity.
   - **Macrophage and helper T cells stimulate B cell production.** In many cases, the antigen will not directly stimulate the proliferation of B cells. Instead, the antigen or antigen-bearing pathogen must first be engulfed by a macrophage. T cells then bind to the macrophage in a cell-mediated response. Interleukins secreted by the helper T cells stimulate the production of B cells.

Humans have learned to supplement natural body defenses. Three important approaches follow:

1. **Antibiotics** are chemicals derived from bacteria or fungi that are harmful to other microorganisms.
2. **Vaccines** are substances that stimulate the production of memory cells. Inactivated viruses or fragments of viruses, bacteria, or other microorganisms are used as vaccines. Once memory cells are formed, the introduction of the live microorganism will stimulate a swift response by the immune system before any disease can become established.
3. **Passive immunity** is obtained by transferring antibodies from an individual who previously had a disease to a newly infected individual. Newborn infants are protected by passive immunity through the transfer of antibodies across the placenta and by antibodies in breast milk.

The Endocrine System

The endocrine system produces **hormones** that help maintain homeostasis and regulate reproduction and development. A hormone is a chemical messenger produced in one part of the body that affects target cells in another part of the body. Hormones have the following general characteristics:

1. Hormones are transported throughout the body in the blood.
2. Minute amounts of hormones can have significant influence on target cells.
3. Hormones may be steroids, peptides, or modified amino acids.

Through the various sensory neurons, the brain—and especially a portion of the forebrain, the hypothalamus—monitors the external environment and internal conditions of the body. As the master integrator of information, the brain may determine that some kind of action is necessary to maintain homeostasis or that conditions are appropriate to activate developmental changes. These actions are initiated by special **neurosecretory cells** that link the hypothalamus and the **pituitary gland,** a gland attached to the base of the hypothalamus. Neurosecretory cells are structured like neurons, but rather than secreting neurotransmitters into synapses that affect neighboring neurons, they secrete hormones into the blood. There are two halves, or lobes, of the pituitary. Their special associations with the hypothalamus are described below:

1. **Posterior pituitary.** Two hormones, **ADH** (**antidiuretic hormone**) and **oxytocin,** are produced by neurosecretory cells in the hypothalamus and are stored in the posterior pituitary and released as needed.
2. **Anterior pituitary. Releasing hormones** are produced by neurosecretory cells in the hypothalamus and secreted into the blood. This blood flows directly to the anterior pituitary where the releasing hormones stimulate the *release* of **tropic hormones** produced in the anterior pituitary. Tropic hormones are hormones whose target cells are other endocrine glands. Thus, they regulate hormone production by other glands.

Because the pituitary gland controls the production of hormones by many other glands, it is often referred to as the "master gland." Clearly, however, it is itself controlled by the hypothalamus. In addition, hormones from the posterior pituitary do not influence other glands, but target specific body tissues.

A summary of various important hormones, their source, and their function is given in Table 12-1.

The regulation of blood glucose concentration in the blood illustrates how the endocrine system maintains homeostasis by the action of antagonistic hormones. Among the cells of the pancreas that produce digestive enzymes, there are bundles of cells called the **islets of Langerhans**, which contain two kinds of cells, **alpha** (α) **cells** and **beta** (β) **cells**. These cells secrete hormones, as follows:

1. **Beta cells secrete insulin**. When the concentration of blood glucose rises (after eating, for example), beta cells secrete insulin into the blood. Insulin stimulates the liver and most other body cells to absorb glucose. Liver and muscle cells convert the glucose to glycogen (for storage), and adipose cells (which form a connective tissue) convert the glucose to fat. In this way, glucose concentration decreases in the blood.
2. **Alpha cells secrete glucagon**. When the concentration of blood glucose drops (during exercise, for example), alpha cells secrete glucagon into the blood. Glucagon stimulates the liver to release glucose. The glucose in the liver originates from the breakdown of glycogen and the conversion of amino acids and fatty acids into glucose.

Another example of antagonistic hormones occurs in the maintenance of Ca^{+} in the blood. Parathyroid hormone (PTH) from the parathyroid glands increases Ca^{2+} in the blood by stimulating Ca^{2+} reabsorption in the kidney and Ca^{2+} release from the bones. Calcitonin from the thyroid gland has the opposite effect on the bones and kidneys.

There are two methods by which hormones are known to trigger activities in target cells, as follows:

1. The hormone (usually a steroid) diffuses through the plasma membrane, through the cytoplasm, and into the nucleus. The hormone *binds to a receptor protein in the nucleus.* The receptor protein, in turn, activates a portion of the DNA that turns on specific genes.

2. The hormone (usually a peptide) *binds to a receptor protein on the plasma membrane* of the cell (**receptor-mediated endocytosis**). The receptor protein, in turn, stimulates the production of one of the following **second messengers.**
   - **Cyclic AMP** (**cAMP**) is produced from ATP. Cyclic AMP, in turn, triggers an enzyme that generates specific cellular changes.
   - **Inositol triphosphate** (**IP_3**) is produced from membrane phospholipids. IP_3, in turn, triggers the release of Ca^{2+} from the endoplasmic reticulum, which, in turn, activates enzymes that generate cellular changes.

Table 12-1

Source	*Hormone*	*Target*	*Action*
Posterior Pituitary	ADH (antidiuretic hormone)	kidneys	increases reabsorption of water
	oxytocin	mammary glands	stimulates release of milk
Anterior Pituitary (tropic hormones)	TSH (thyroid stimulating hormone)	thyroid	secretion of T_4 and T_3
	ACTH (adrenocorticotropic hormone)	adrenal cortex	secretion of glucocorticoids
	FSH (follicle stimulating hormone)	ovaries, testes	regulates oogenesis and spermatogenesis
	LH (luteinizing hormone)	ovaries, testes	regulates oogenesis and spermatogenesis
Anterior Pituitary (hormones)	PRL (prolactin)	mammary glands	production of milk
	GH (growth hormone)	bone, muscle	stimulates growth
Pancreas (alpha cells)	glucagon	liver	increases blood glucose
Pancreas (beta cells)	insulin	liver, muscles, fat	lowers blood glucose
Adrenal gland (medulla)	epinephrine (adrenalin) and norepinephrine (noradrenalin)	blood vessels, liver and heart	increases blood glucose, constricts blood vessels (fight or flight response)
Adrenal gland (cortex)	glucocorticoids (e.g., cortisol)	general	increases blood glucose
	mineralocorticoids (e.g., aldosterone)	kidney	increases reabsorption of Na^+ and excretion of K^+
Thyroid	T_4 (thyroxin) and T_3 (triiodothyronine)	general	increases cellular metabolism
	calcitonin	bone	lowers blood Ca^{2+}
Parathyroid	PTH (parathyroid hormone)	bone	increases blood Ca^{2+}
Testis	testosterone	testes, general	spermatogenesis, secondary sex characteristics
Ovary	estrogen	uterus, general	menstrual cycle, secondary sex characteristics
	progesteron	uterus	menstrual cycle, pregnancy
Pineal	melatonin	body	circadian rhythms