LECTURE PRESENTATIONS

For CAMPBELL BIOLOGY, NINTH EDITION

Jane B. Reece, Lisa A. Urry, Michael L. Cain, Steven A. Wasserman, Peter V. Minorsky, Robert B. Jackson

Chapter 42

Circulation and Gas Exchange

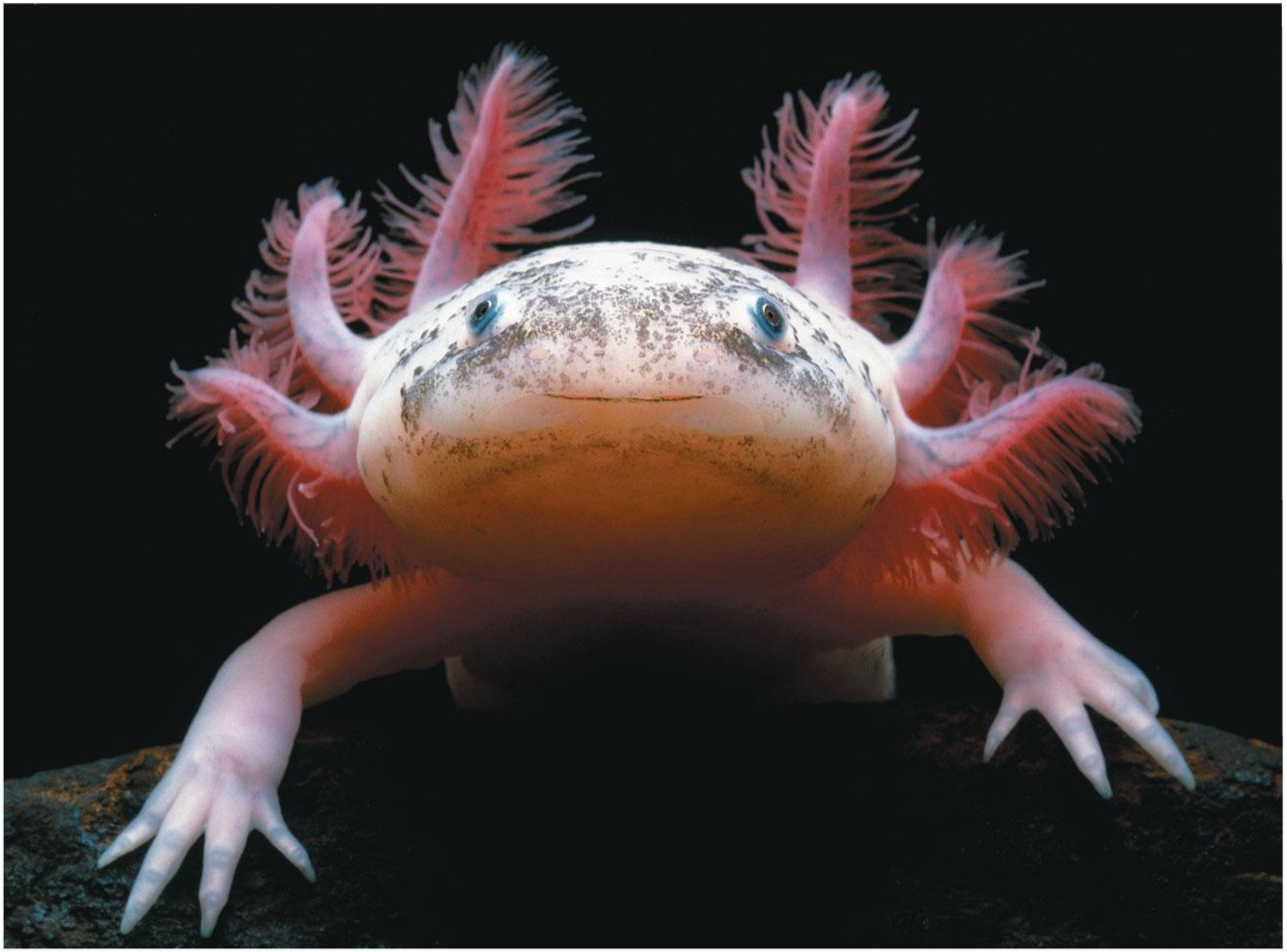
Lectures by
Erin Barley
Kathleen Fitzpatrick

Overview: Trading Places

- Every organism must exchange materials with its environment
- Exchanges ultimately occur at the cellular level by crossing the plasma membrane
- In unicellular organisms, these exchanges occur directly with the environment

- For most cells making up multicellular organisms, direct exchange with the environment is not possible
- Gills are an example of a specialized exchange system in animals
  - O_2 diffuses from the water into blood vessels
  - CO_2 diffuses from blood into the water
- Internal transport and gas exchange are functionally related in most animals

Figure 42.1



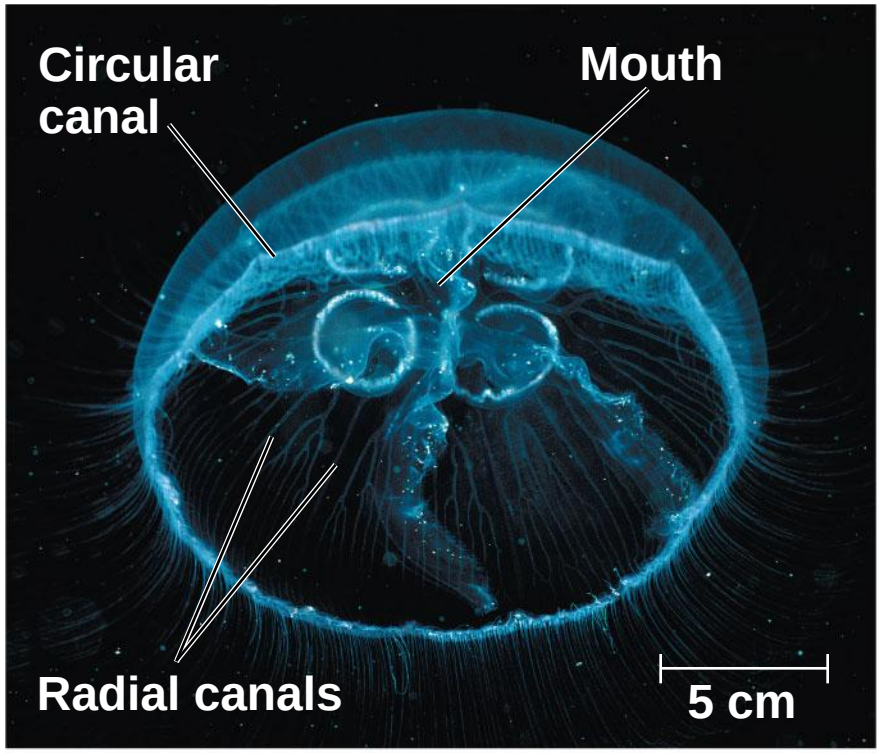
Concept 42.1: Circulatory systems link exchange surfaces with cells throughout the body

- Diffusion time is proportional to the square of the distance
- Diffusion is only efficient over small distances
- In small and/or thin animals, cells can exchange materials directly with the surrounding medium
- In most animals, cells exchange materials with the environment via a fluid-filled circulatory system

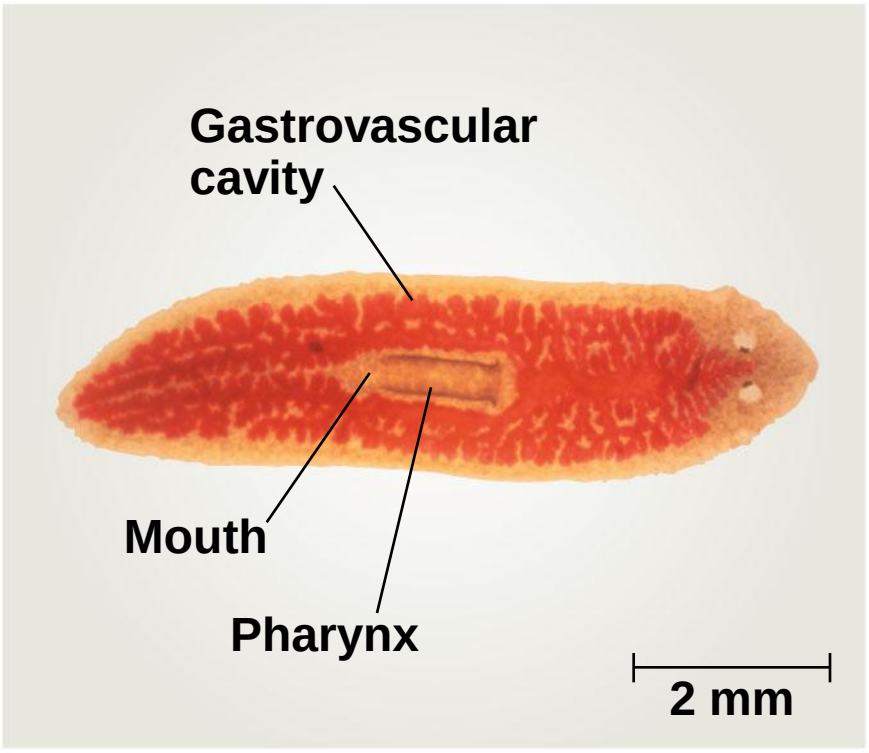
Gastrovascular Cavities

- Some animals lack a circulatory system
- Some cnidarians, such as jellies, have elaborate gastrovascular cavities
- A gastrovascular cavity functions in both digestion and distribution of substances throughout the body
- The body wall that encloses the gastrovascular cavity is only two cells thick
- Flatworms have a gastrovascular cavity and a large surface area to volume ratio

Figure 42.2



(a) The moon jelly *Aurelia*, a cnidarian



(b) The planarian *Dugesia*, a flatworm

Evolutionary Variation in Circulatory Systems

- A circulatory system minimizes the diffusion distance in animals with many cell layers

General Properties of Circulatory Systems

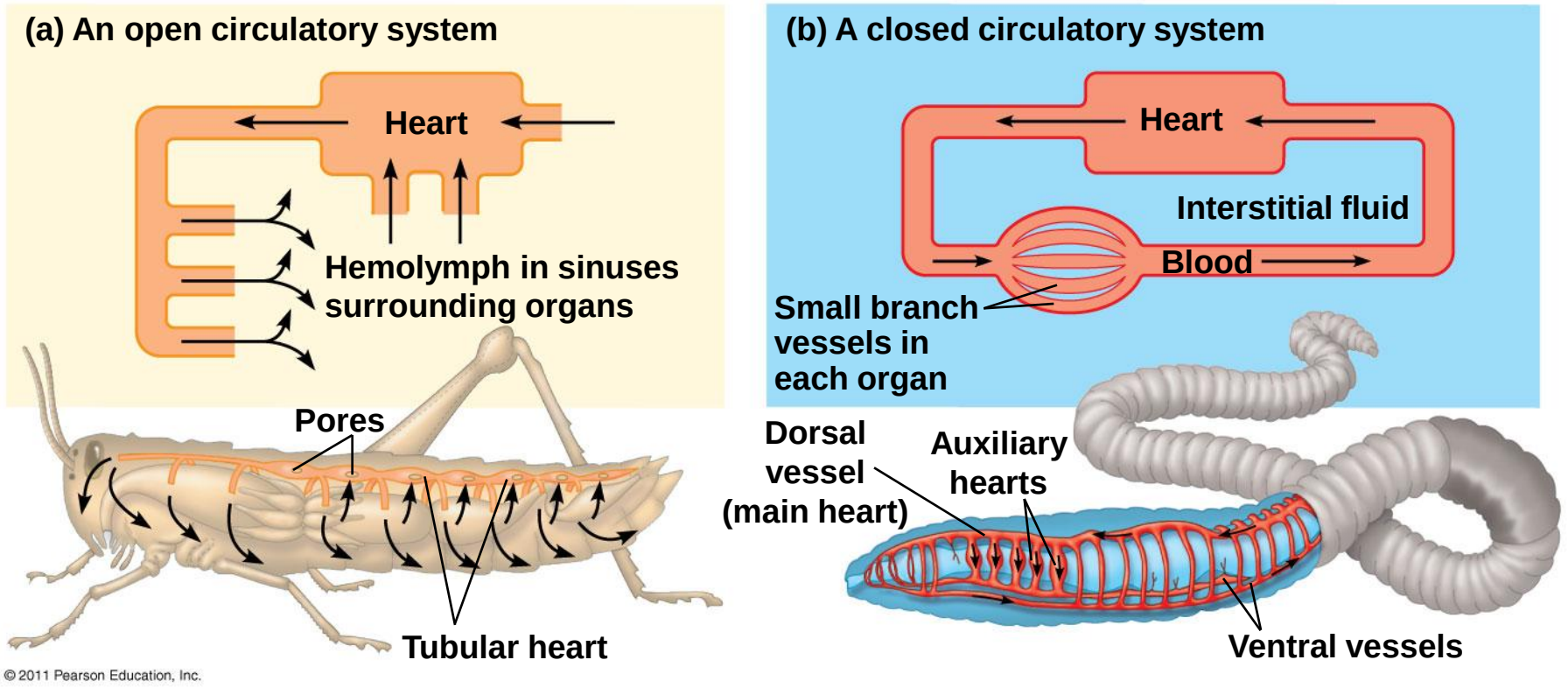
- A circulatory system has
  - A circulatory fluid
  - A set of interconnecting vessels
  - A muscular pump, the **heart**
- The circulatory system connects the fluid that surrounds cells with the organs that exchange gases, absorb nutrients, and dispose of wastes
- Circulatory systems can be open or closed and vary in the number of circuits in the body

Open and Closed Circulatory Systems

- In insects, other arthropods, and most molluscs, blood bathes the organs directly in an **open circulatory system**
- In an open circulatory system, there is no distinction between blood and interstitial fluid, and this general body fluid is called **hemolymph**

- In a **closed circulatory system**, **blood** is confined to vessels and is distinct from the interstitial fluid
- Closed systems are more efficient at transporting circulatory fluids to tissues and cells
- Annelids, cephalopods, and vertebrates have closed circulatory systems

Figure 42.3



Organization of Vertebrate Circulatory Systems

- Humans and other vertebrates have a closed circulatory system called the **cardiovascular system**
- The three main types of blood vessels are arteries, veins, and capillaries
- Blood flow is one way in these vessels

- **Arteries** branch into **arterioles** and carry blood away from the heart to **capillaries**
- Networks of capillaries called **capillary beds** are the sites of chemical exchange between the blood and interstitial fluid
- **Venules** converge into **veins** and return blood from capillaries to the heart

- Arteries and veins are distinguished by the direction of blood flow, not by O_2 content
- Vertebrate hearts contain two or more chambers
- Blood enters through an **atrium** and is pumped out through a **ventricle**

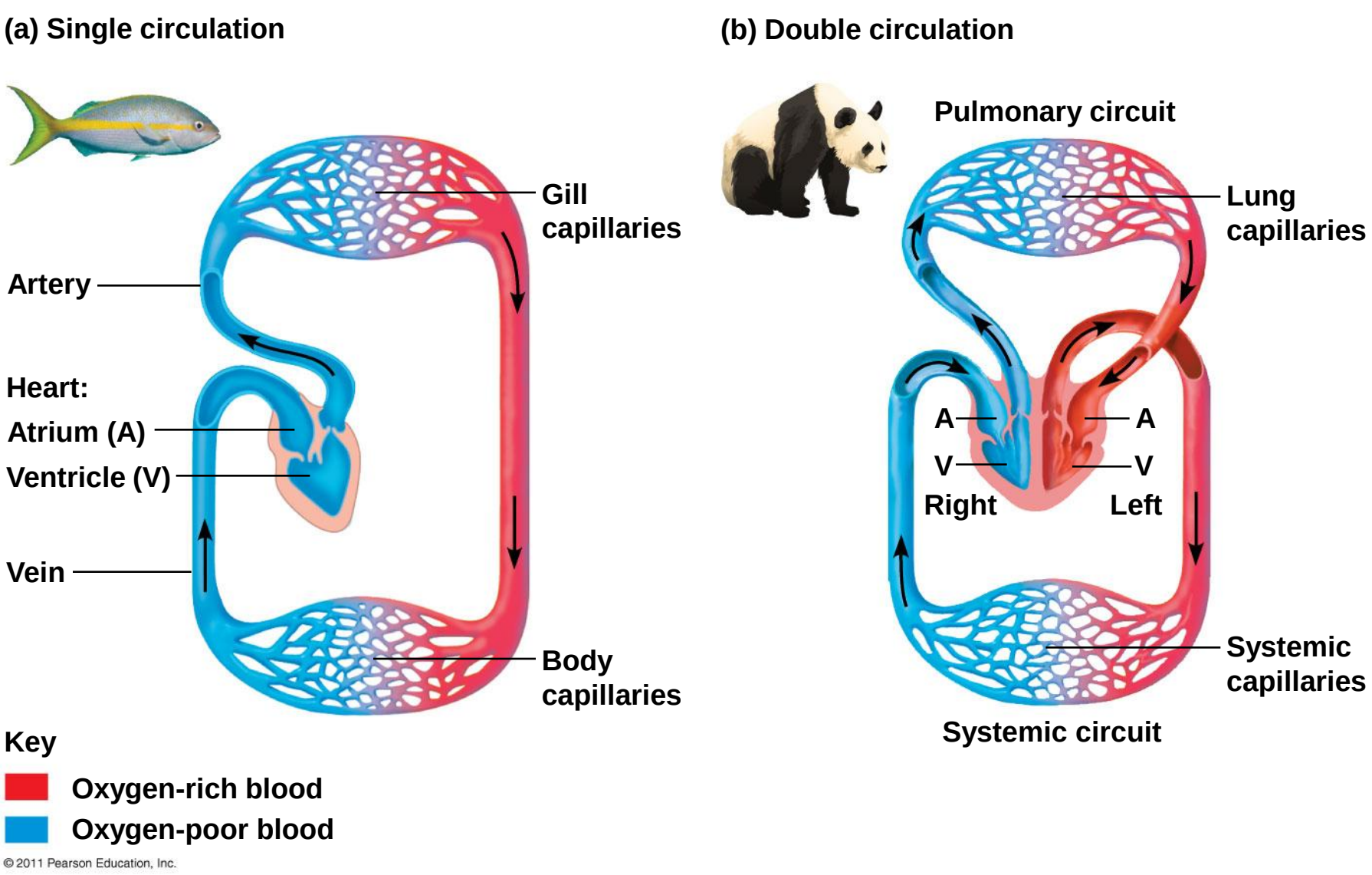
Single Circulation

- Bony fishes, rays, and sharks have single circulation with a two-chambered heart
- In **single circulation**, blood leaving the heart passes through two capillary beds before returning

Double Circulation

- Amphibian, reptiles, and mammals have **double circulation**
- Oxygen-poor and oxygen-rich blood are pumped separately from the right and left sides of the heart

Figure 42.4



- In reptiles and mammals, oxygen-poor blood flows through the **pulmonary circuit** to pick up oxygen through the lungs
- In amphibians, oxygen-poor blood flows through a **pulmocutaneous circuit** to pick up oxygen through the lungs and skin
- Oxygen-rich blood delivers oxygen through the **systemic circuit**
- Double circulation maintains higher blood pressure in the organs than does single circulation

Adaptations of Double Circulatory Systems

- Hearts vary in different vertebrate groups

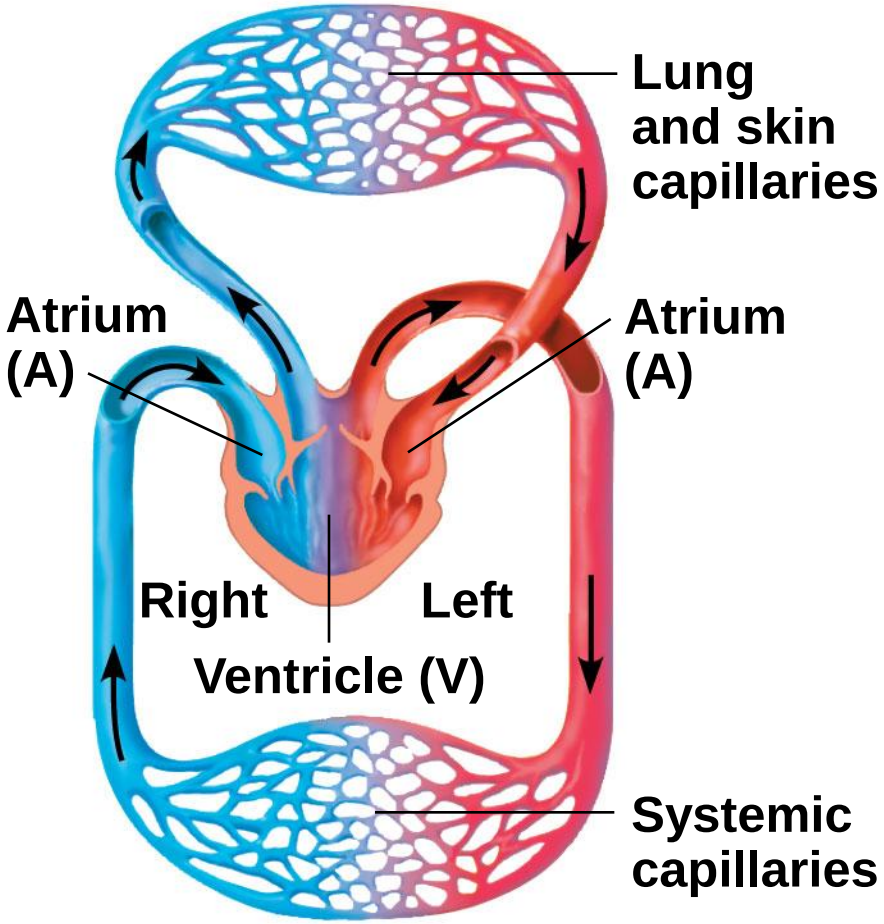
Amphibians

- Frogs and other amphibians have a three-chambered heart: two atria and one ventricle
- The ventricle pumps blood into a forked artery that splits the ventricle's output into the pulmocutaneous circuit and the systemic circuit
- When underwater, blood flow to the lungs is nearly shut off

Figure 42.5a

Amphibians

Pulmocutaneous circuit



Systemic circuit

Key

Oxygen-rich blood

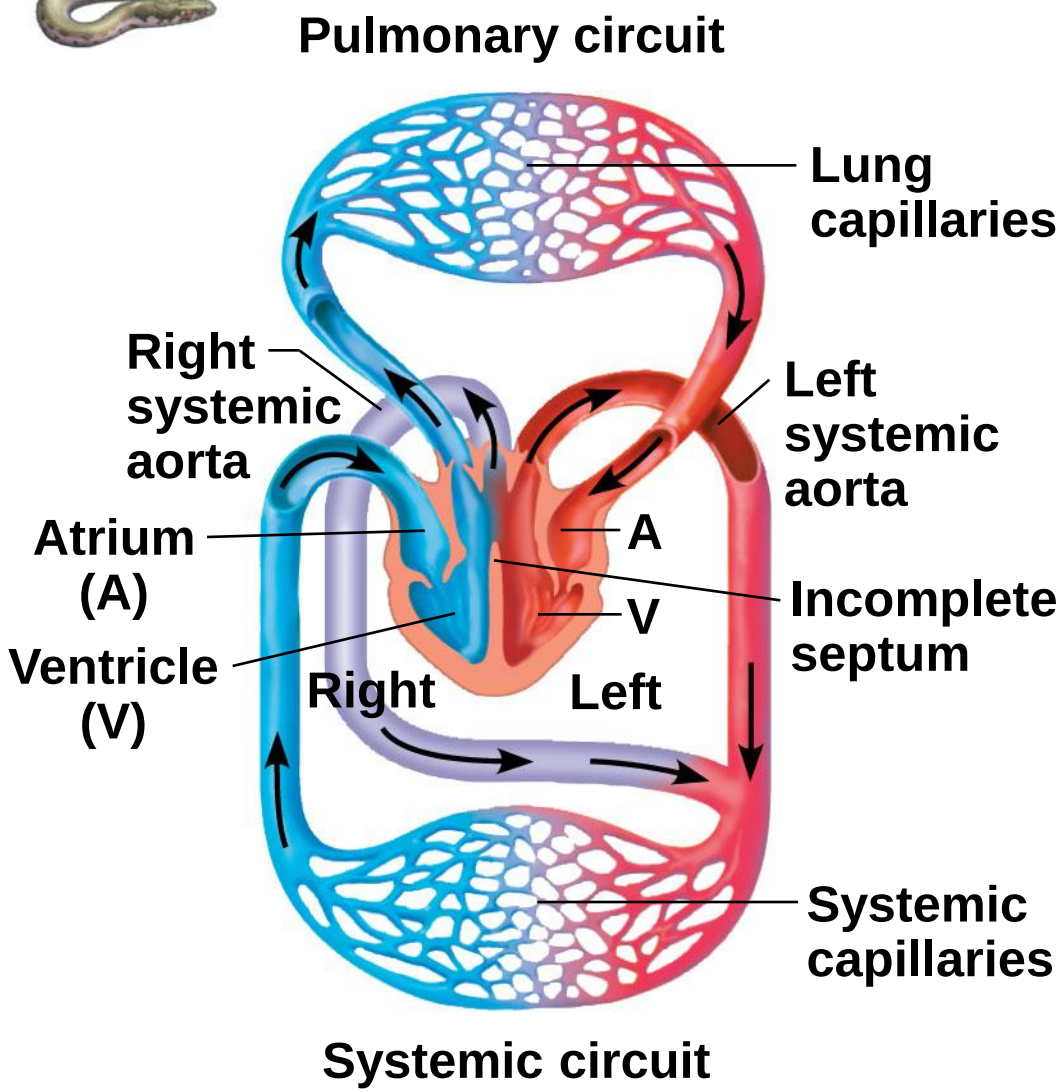
Oxygen-poor blood

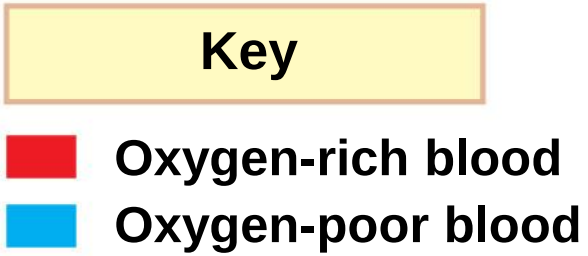
Reptiles (Except Birds)

- Turtles, snakes, and lizards have a three-chambered heart: two atria and one ventricle
- In alligators, caimans, and other crocodilians a septum divides the ventricle
- Reptiles have double circulation, with a pulmonary circuit (lungs) and a systemic circuit

Figure 42.5b

Reptiles (Except Birds)





Mammals and Birds

- Mammals and birds have a four-chambered heart with two atria and two ventricles
- The left side of the heart pumps and receives only oxygen-rich blood, while the right side receives and pumps only oxygen-poor blood
- Mammals and birds are endotherms and require more O_2 than ectotherms

Figure 42.5c

Mammals and Birds

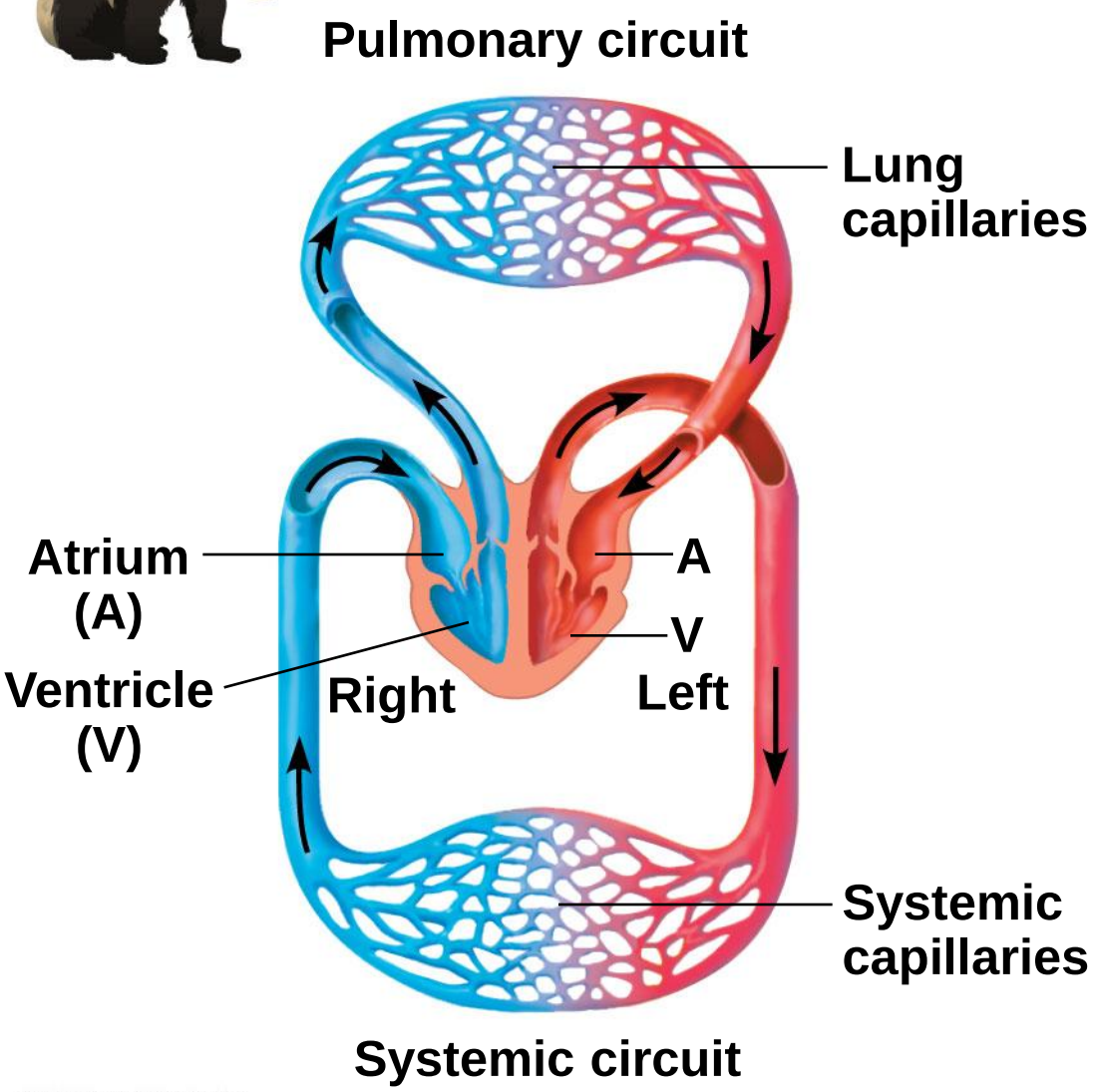
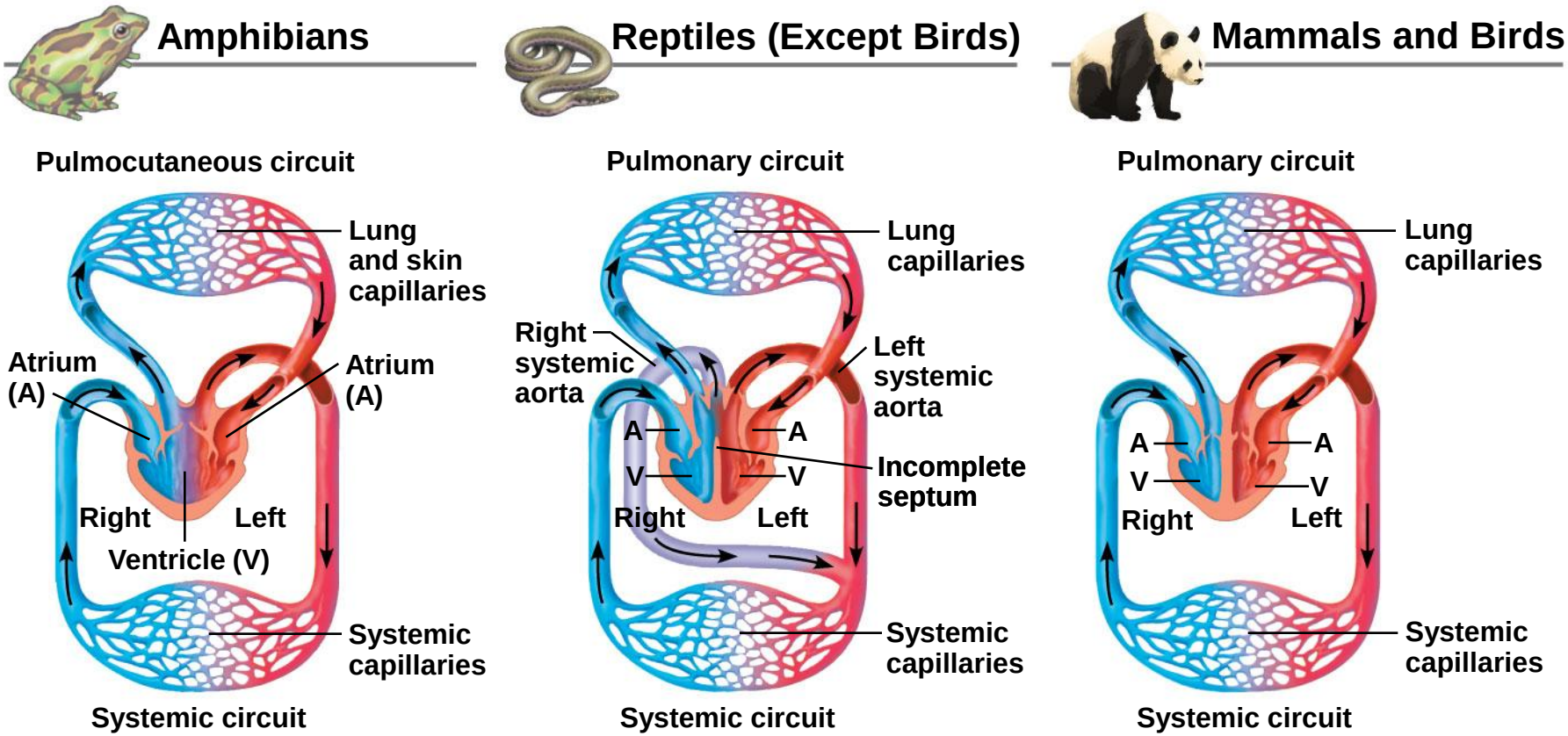


Figure 42.5



Concept 42.2: Coordinated cycles of heart contraction drive double circulation in mammals

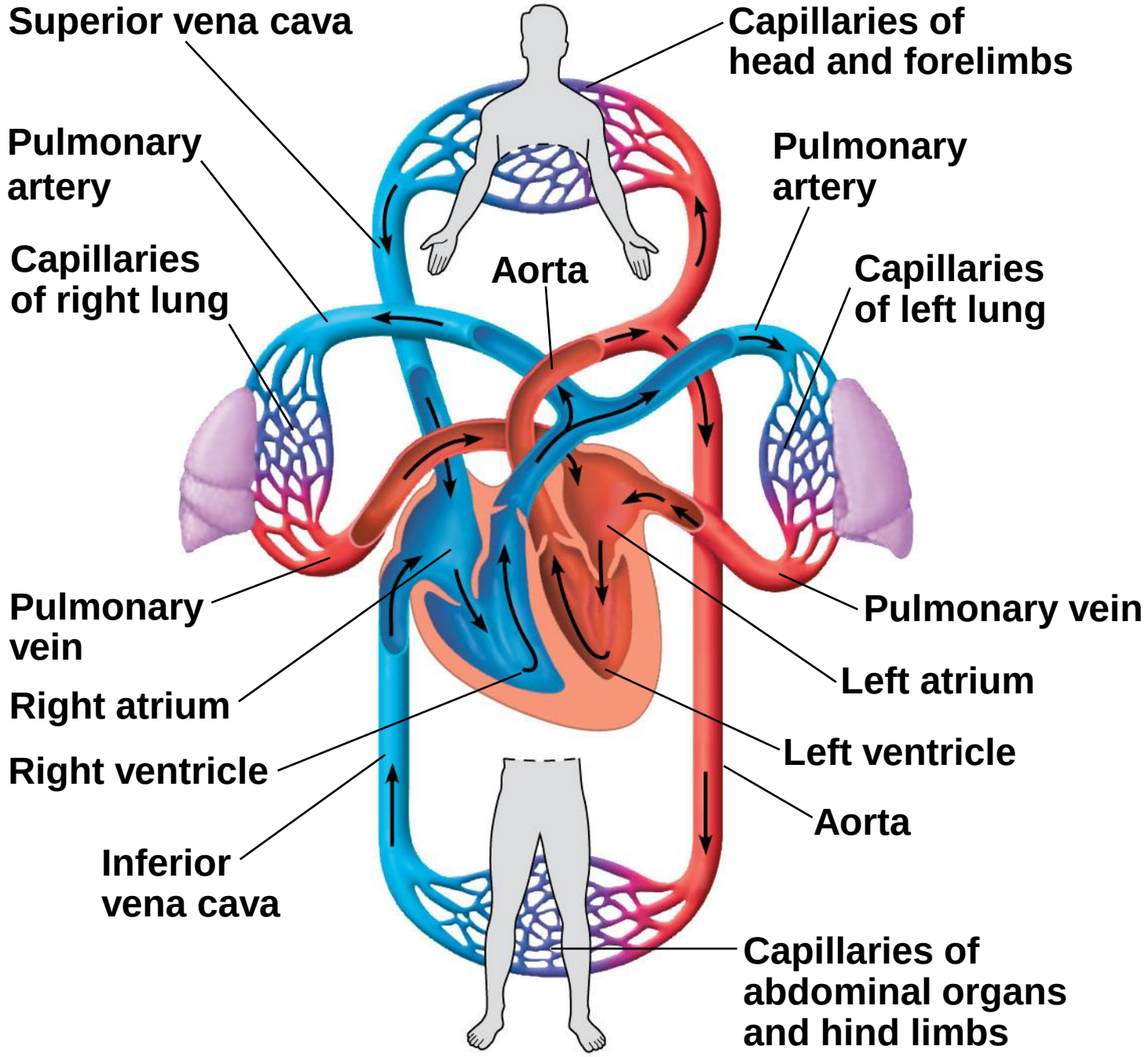
- The mammalian cardiovascular system meets the body's continuous demand for O_2

Mammalian Circulation

- Blood begins its flow with the right ventricle pumping blood to the lungs
- In the lungs, the blood loads O_2 and unloads CO_2
- Oxygen-rich blood from the lungs enters the heart at the left atrium and is pumped through the aorta to the body tissues by the left ventricle
- The aorta provides blood to the heart through the coronary arteries

- Blood returns to the heart through the superior vena cava (blood from head, neck, and forelimbs) and inferior vena cava (blood from trunk and hind limbs)
- The superior vena cava and inferior vena cava flow into the right atrium

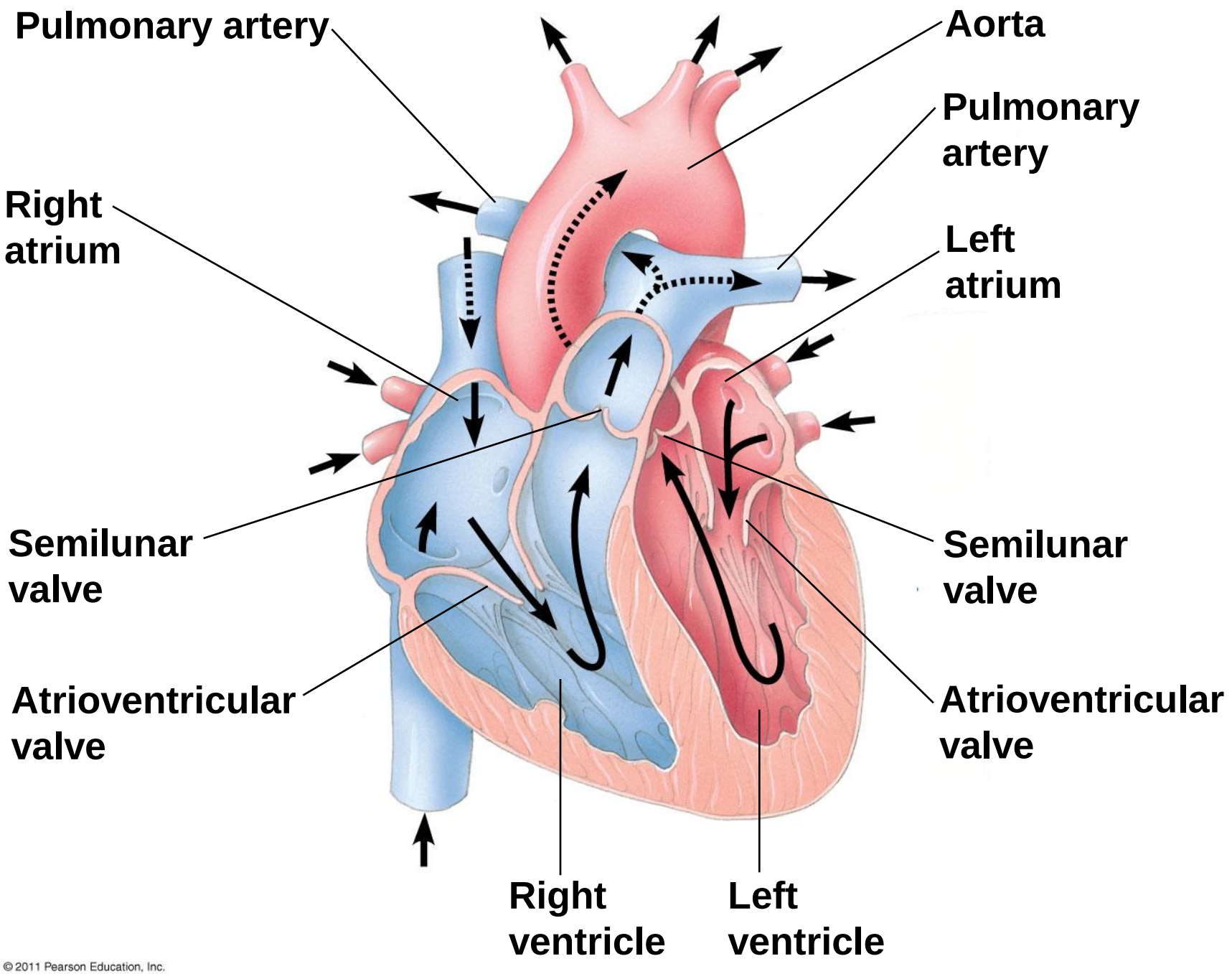
Figure 42.6



The Mammalian Heart: *A Closer Look*

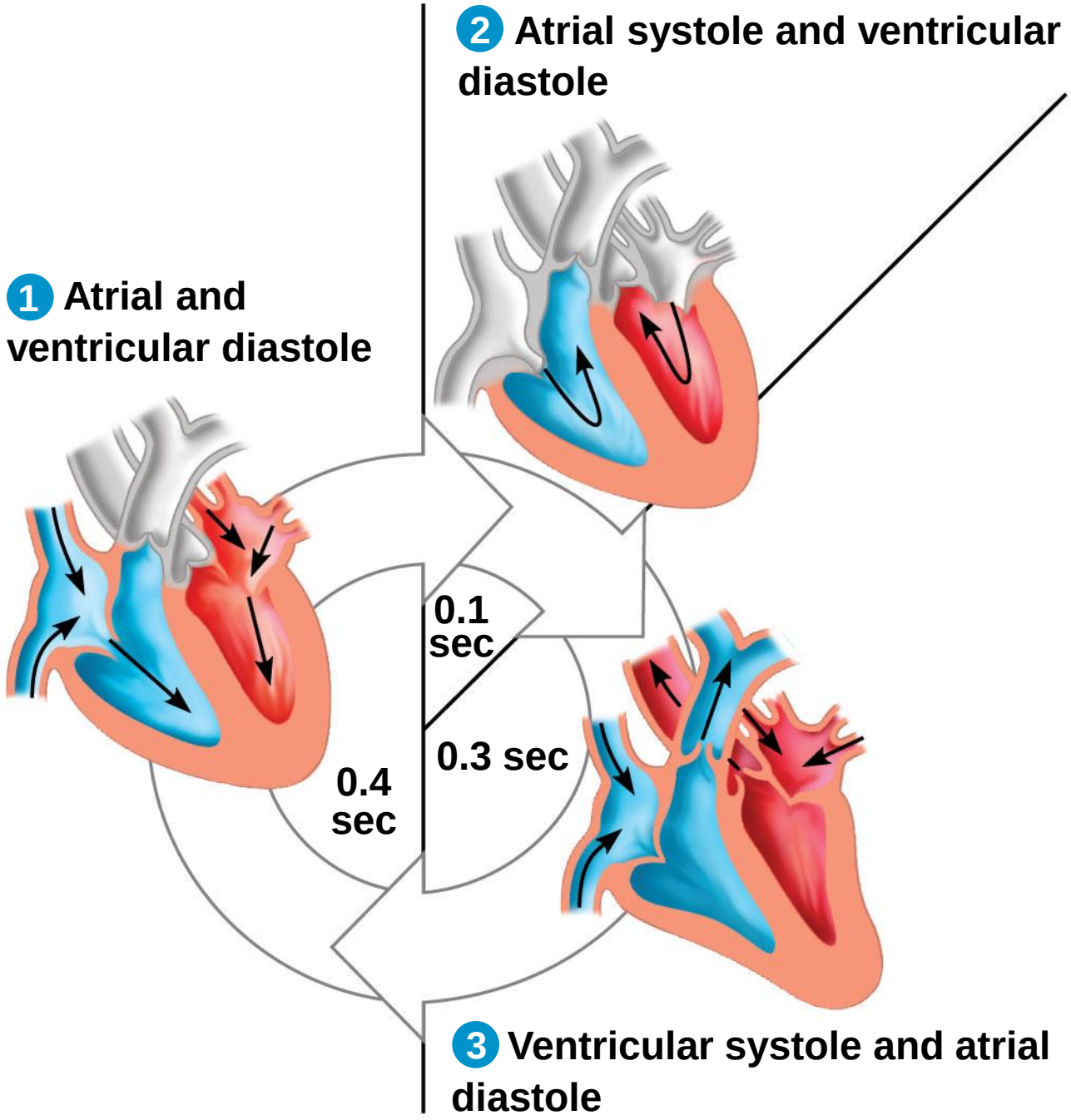
- A closer look at the mammalian heart provides a better understanding of double circulation

Figure 42.7



- The heart contracts and relaxes in a rhythmic cycle called the **cardiac cycle**
- The contraction, or pumping, phase is called **systole**
- The relaxation, or filling, phase is called **diastole**

Figure 42.8-3



- The **heart rate**, also called the pulse, is the number of beats per minute
- The **stroke volume** is the amount of blood pumped in a single contraction
- The **cardiac output** is the volume of blood pumped into the systemic circulation per minute and depends on both the heart rate and stroke volume

- Four valves prevent backflow of blood in the heart
- The **atrioventricular (AV) valves** separate each atrium and ventricle
- The **semilunar valves** control blood flow to the aorta and the pulmonary artery

- The “lub-dup” sound of a heart beat is caused by the recoil of blood against the AV valves (lub) then against the semilunar (dup) valves
- Backflow of blood through a defective valve causes a **heart murmur**

Maintaining the Heart's Rhythmic Beat

- Some cardiac muscle cells are self-excitable, meaning they contract without any signal from the nervous system
- The **sinoatrial (SA) node**, or pacemaker, sets the rate and timing at which cardiac muscle cells contract
- Impulses that travel during the cardiac cycle can be recorded as an **electrocardiogram** (**ECG** or **EKG**)

Figure 42.9-1

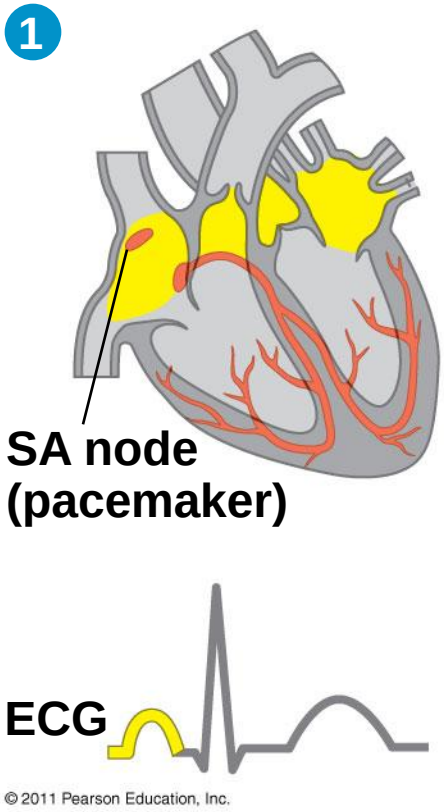


Figure 42.9-2

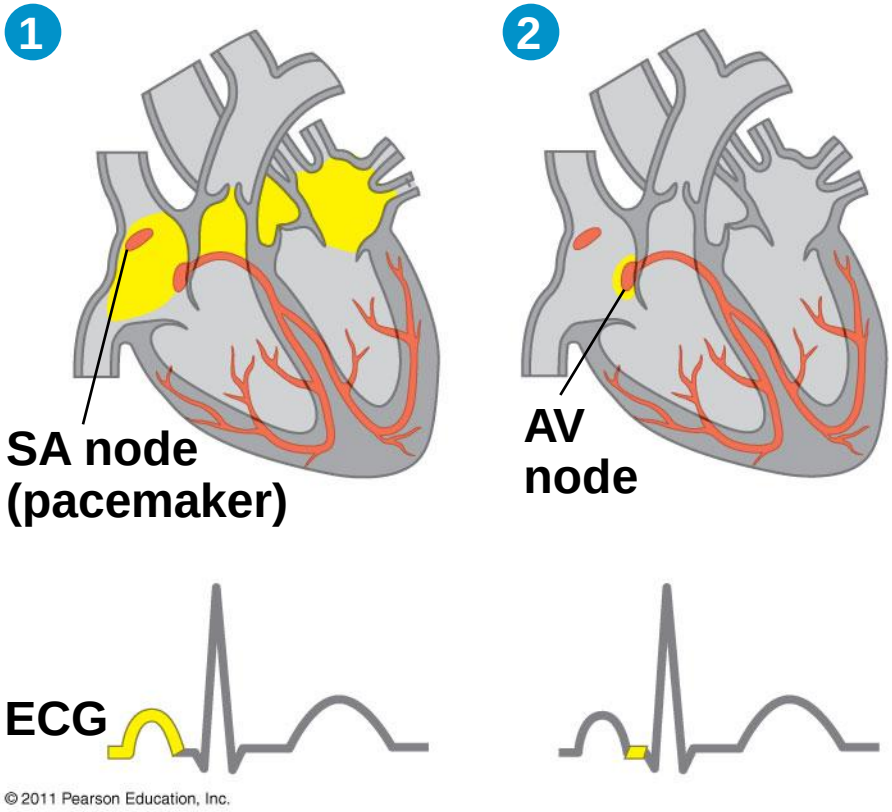


Figure 42.9-3

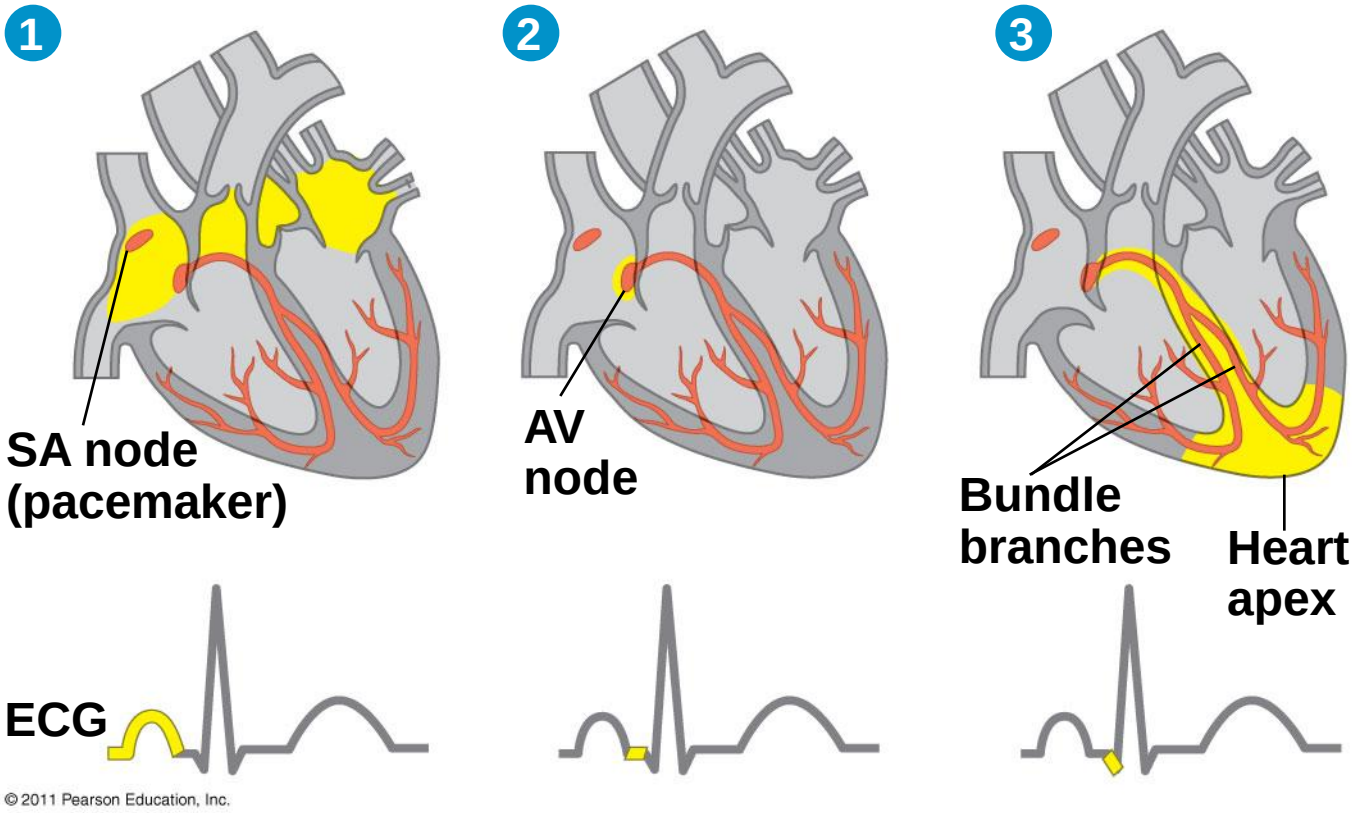
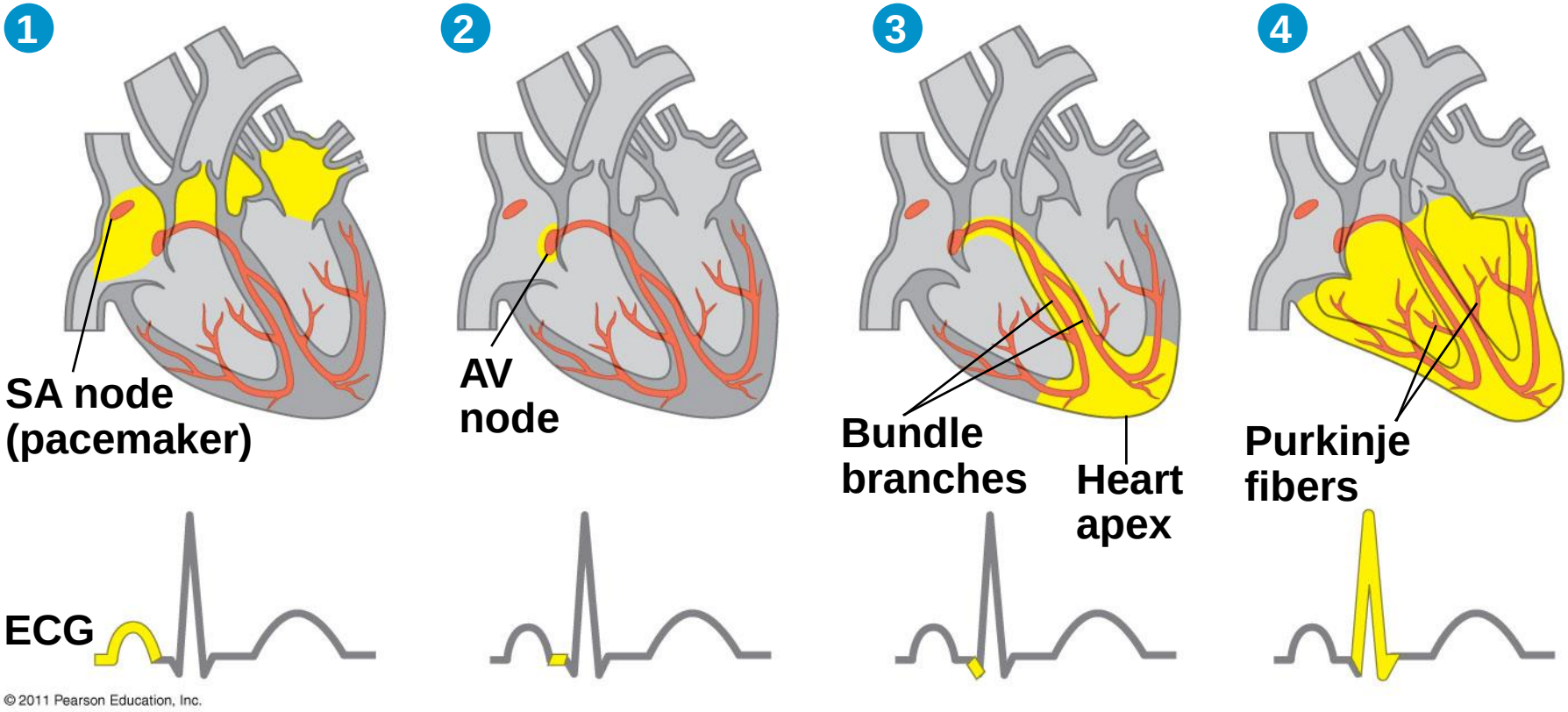


Figure 42.9-4



- Impulses from the SA node travel to the **atrioventricular (AV) node**
- At the AV node, the impulses are delayed and then travel to the Purkinje fibers that make the ventricles contract

- The pacemaker is regulated by two portions of the nervous system: the sympathetic and parasympathetic divisions
- The sympathetic division speeds up the pacemaker
- The parasympathetic division slows down the pacemaker
- The pacemaker is also regulated by hormones and temperature

Concept 42.3: Patterns of blood pressure and flow reflect the structure and arrangement of blood vessels

- The physical principles that govern movement of water in plumbing systems also influence the functioning of animal circulatory systems

Blood Vessel Structure and Function

- A vessel's cavity is called the central lumen
- The epithelial layer that lines blood vessels is called the **endothelium**
- The endothelium is smooth and minimizes resistance

Figure 42.10

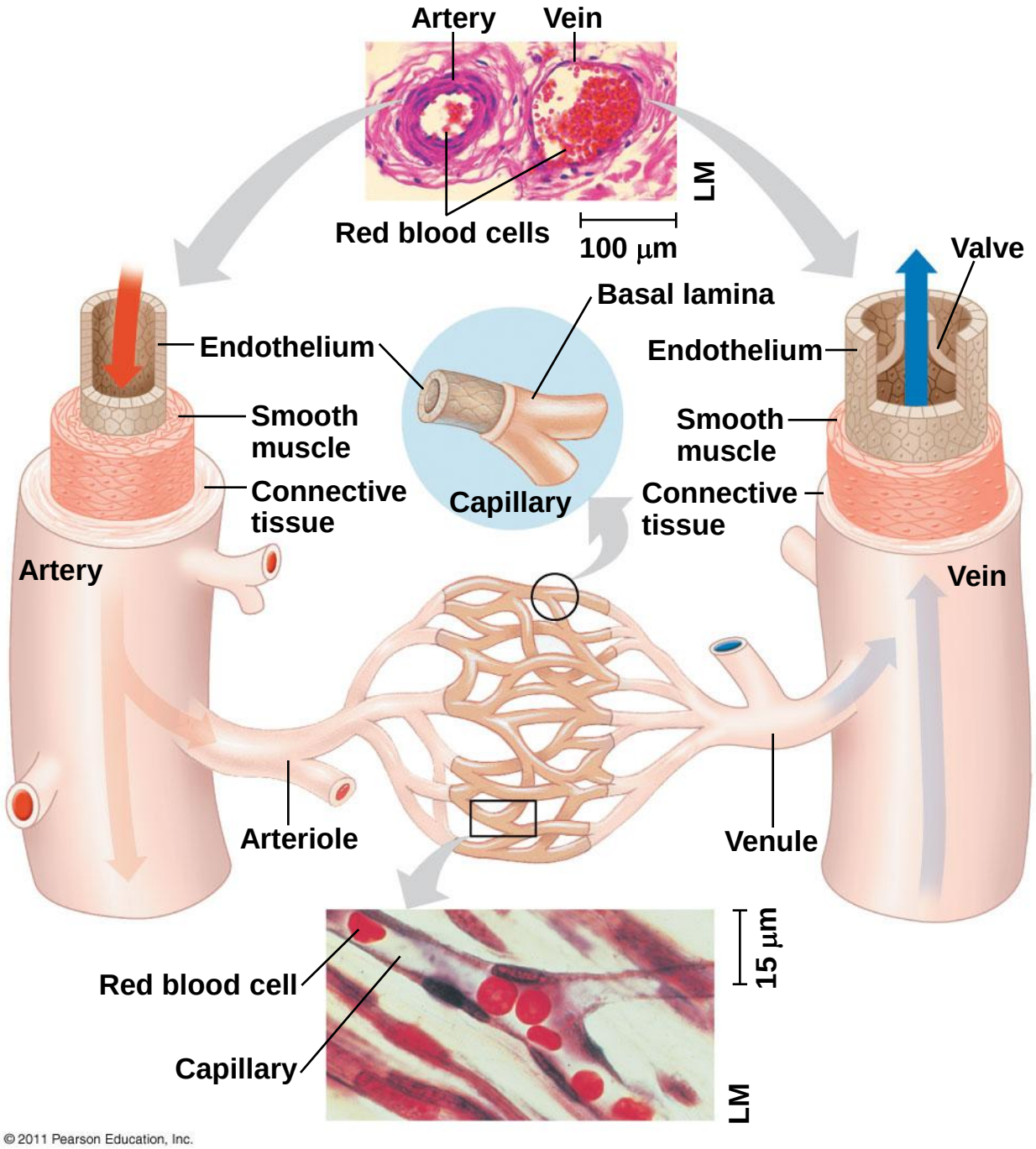


Figure 42.10a

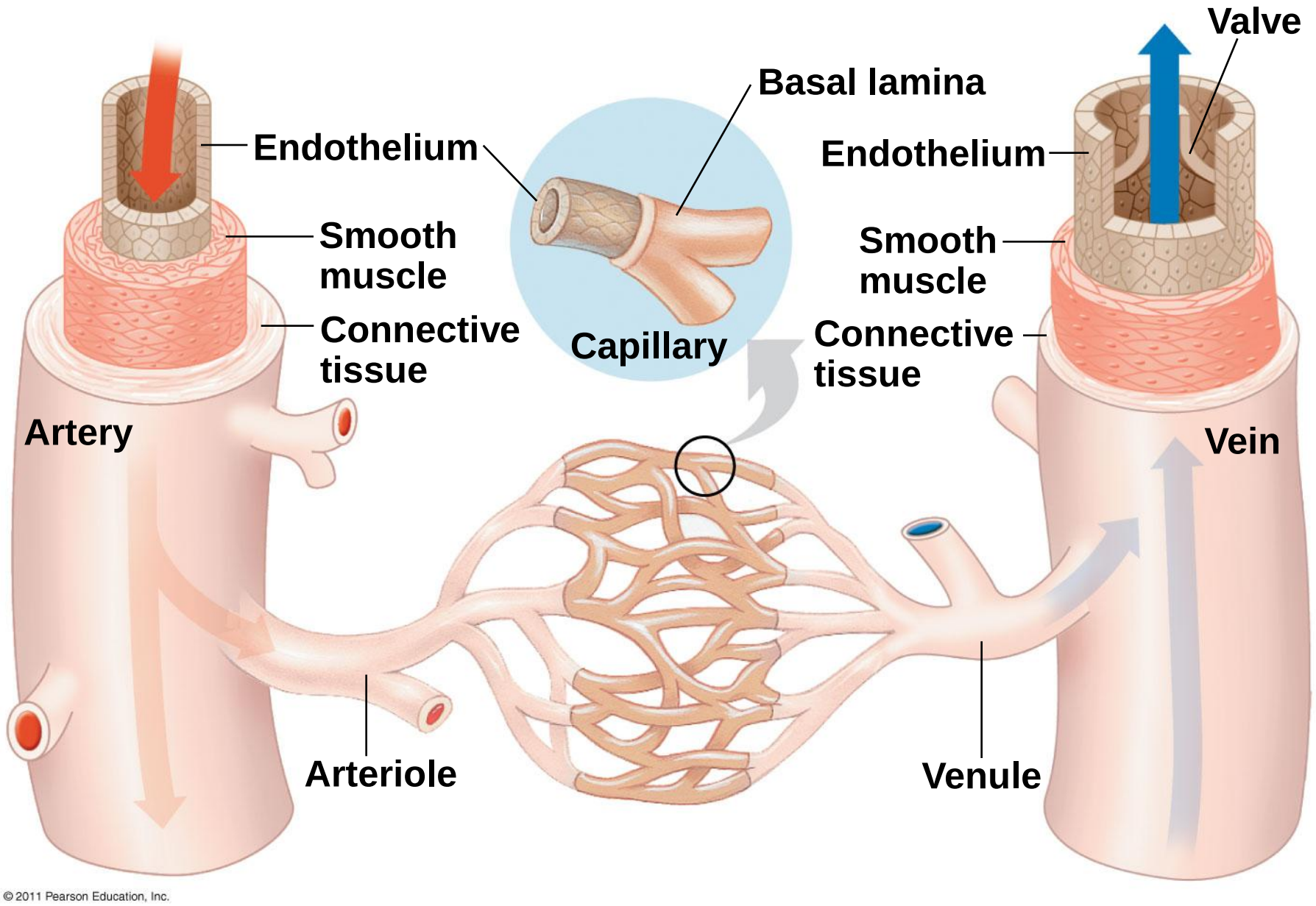


Figure 42.10b

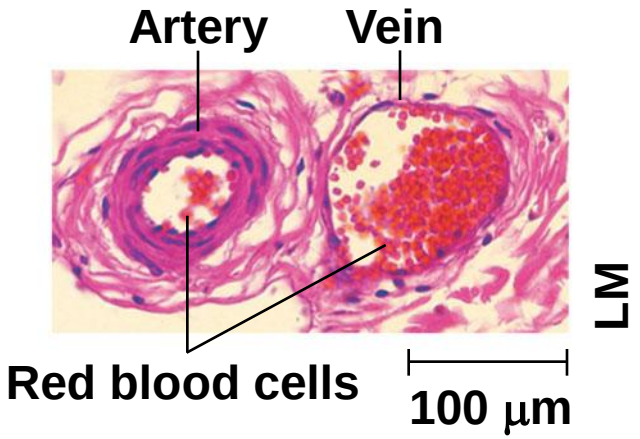
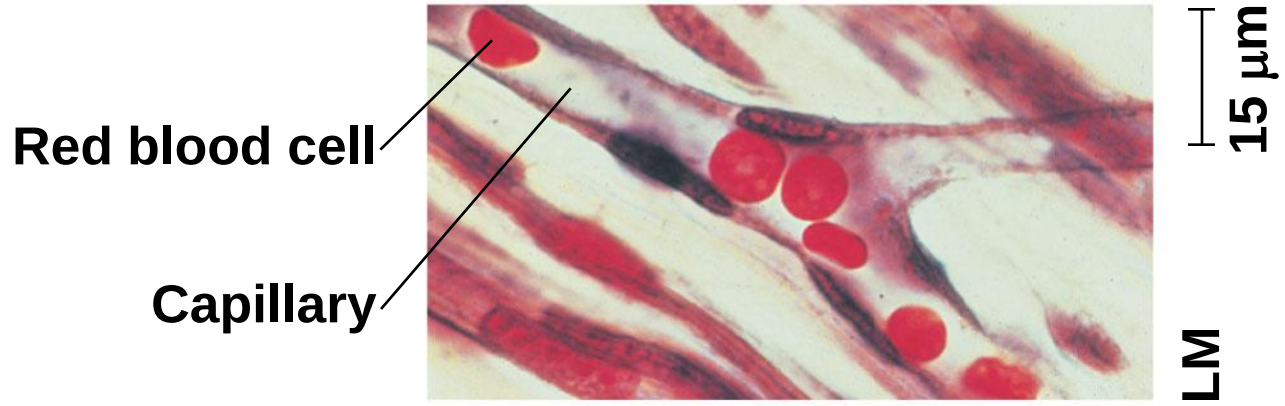


Figure 42.10c

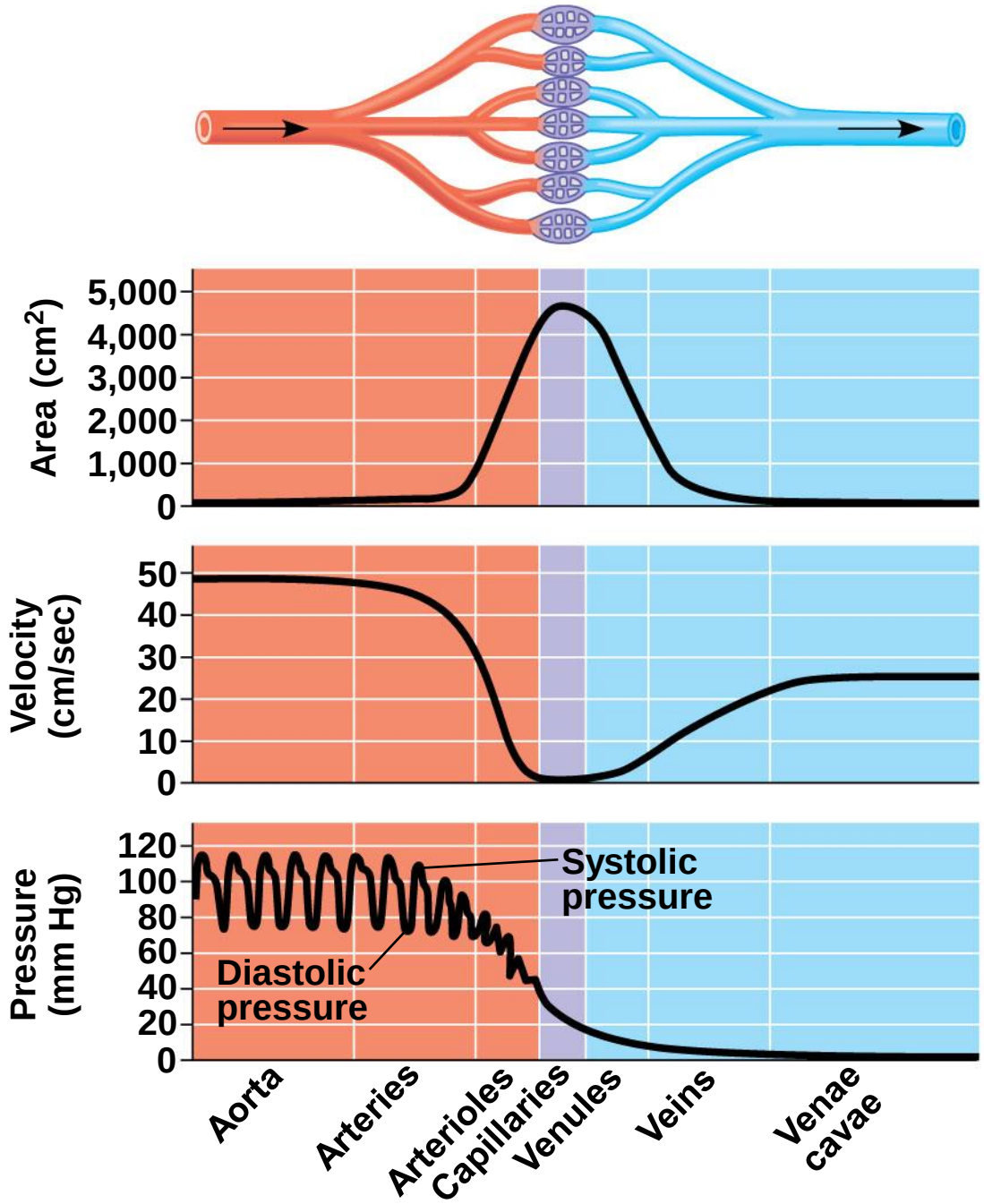


- Capillaries have thin walls, the endothelium plus its basal lamina, to facilitate the exchange of materials
- Arteries and veins have an endothelium, smooth muscle, and connective tissue
- Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart
- In the thinner-walled veins, blood flows back to the heart mainly as a result of muscle action

Blood Flow Velocity

- Physical laws governing movement of fluids through pipes affect blood flow and blood pressure
- Velocity of blood flow is slowest in the capillary beds, as a result of the high resistance and large total cross-sectional area
- Blood flow in capillaries is necessarily slow for exchange of materials

Figure 42.11



Blood Pressure

- Blood flows from areas of higher pressure to areas of lower pressure
- Blood pressure is the pressure that blood exerts against the wall of a vessel
- In rigid vessels blood pressure is maintained; less rigid vessels deform and blood pressure is lost

Changes in Blood Pressure During the Cardiac Cycle

- **Systolic pressure** is the pressure in the arteries during ventricular systole; it is the highest pressure in the arteries
- **Diastolic pressure** is the pressure in the arteries during diastole; it is lower than systolic pressure
- A **pulse** is the rhythmic bulging of artery walls with each heartbeat

Regulation of Blood Pressure

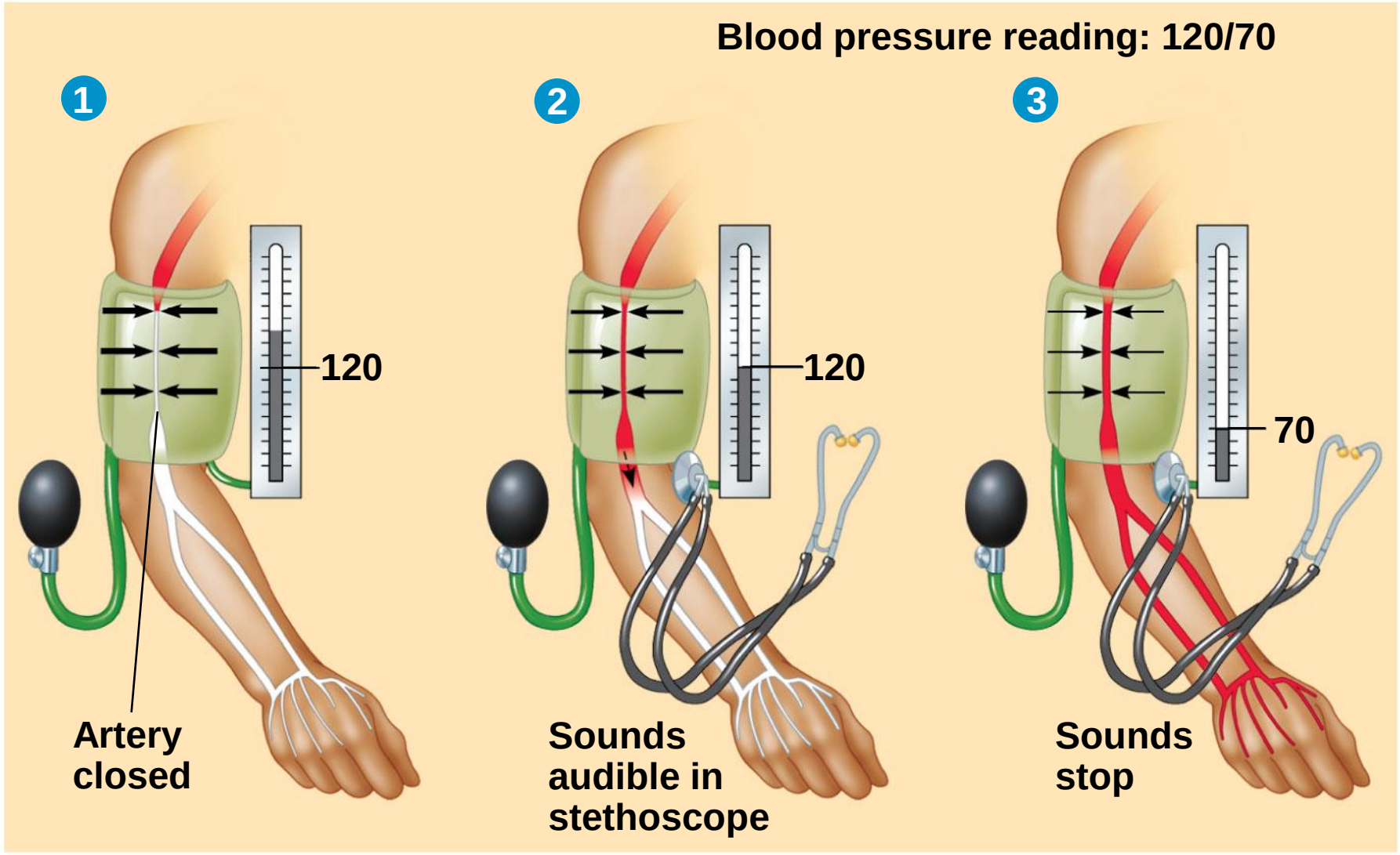
- Blood pressure is determined by cardiac output and peripheral resistance due to constriction of arterioles
- **Vasoconstriction** is the contraction of smooth muscle in arteriole walls; it increases blood pressure
- **Vasodilation** is the relaxation of smooth muscles in the arterioles; it causes blood pressure to fall

- Vasoconstriction and vasodilation help maintain adequate blood flow as the body's demands change
- Nitric oxide is a major inducer of vasodilation
- The peptide endothelin is an important inducer of vasoconstriction

Blood Pressure and Gravity

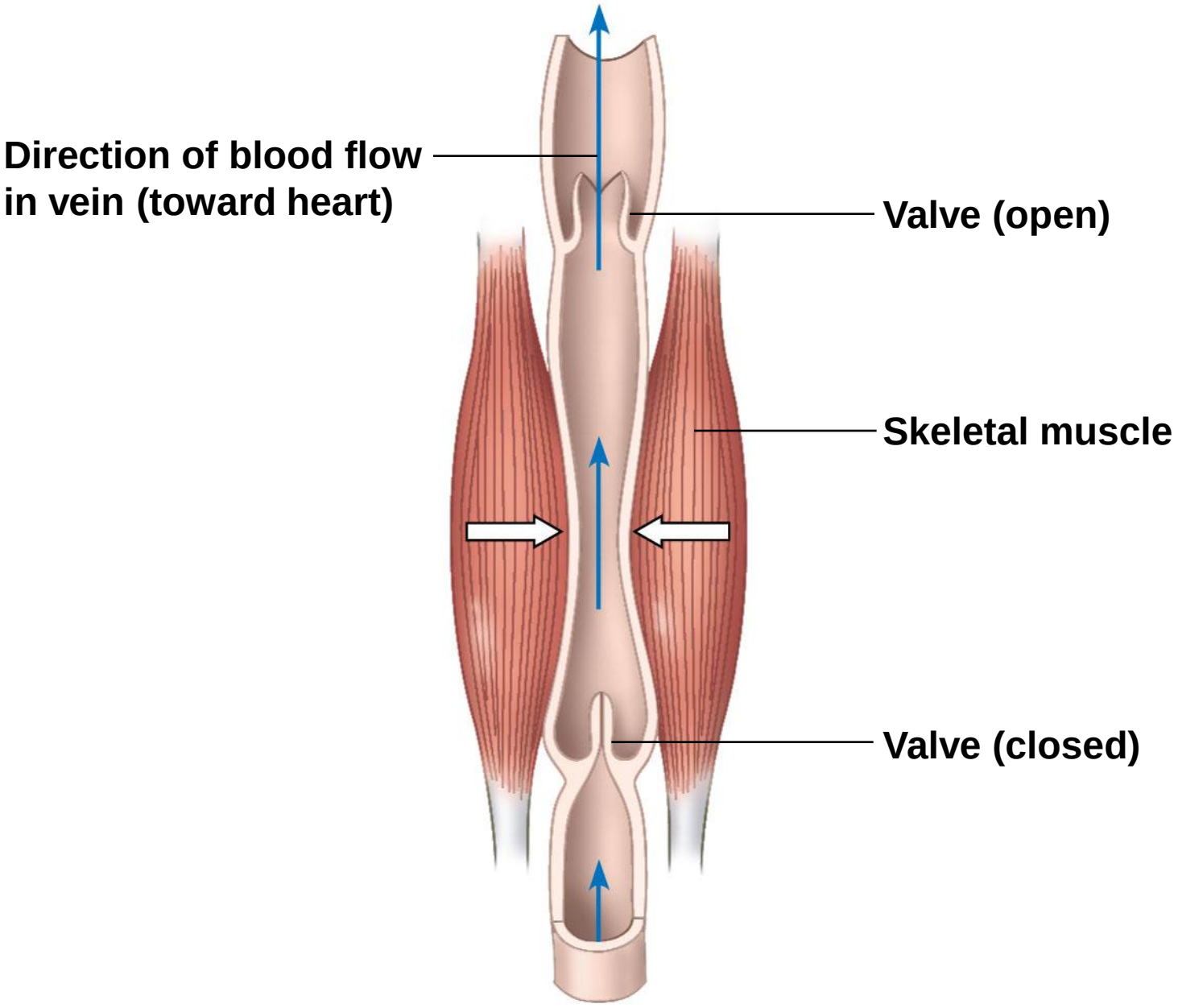
- Blood pressure is generally measured for an artery in the arm at the same height as the heart
- Blood pressure for a healthy 20-year-old at rest is 120 mm Hg at systole and 70 mm Hg at diastole

Figure 42.12



- Fainting is caused by inadequate blood flow to the head
- Animals with longer necks require a higher systolic pressure to pump blood a greater distance against gravity
- Blood is moved through veins by smooth muscle contraction, skeletal muscle contraction, and expansion of the vena cava with inhalation
- One-way valves in veins prevent backflow of blood

Figure 42.13

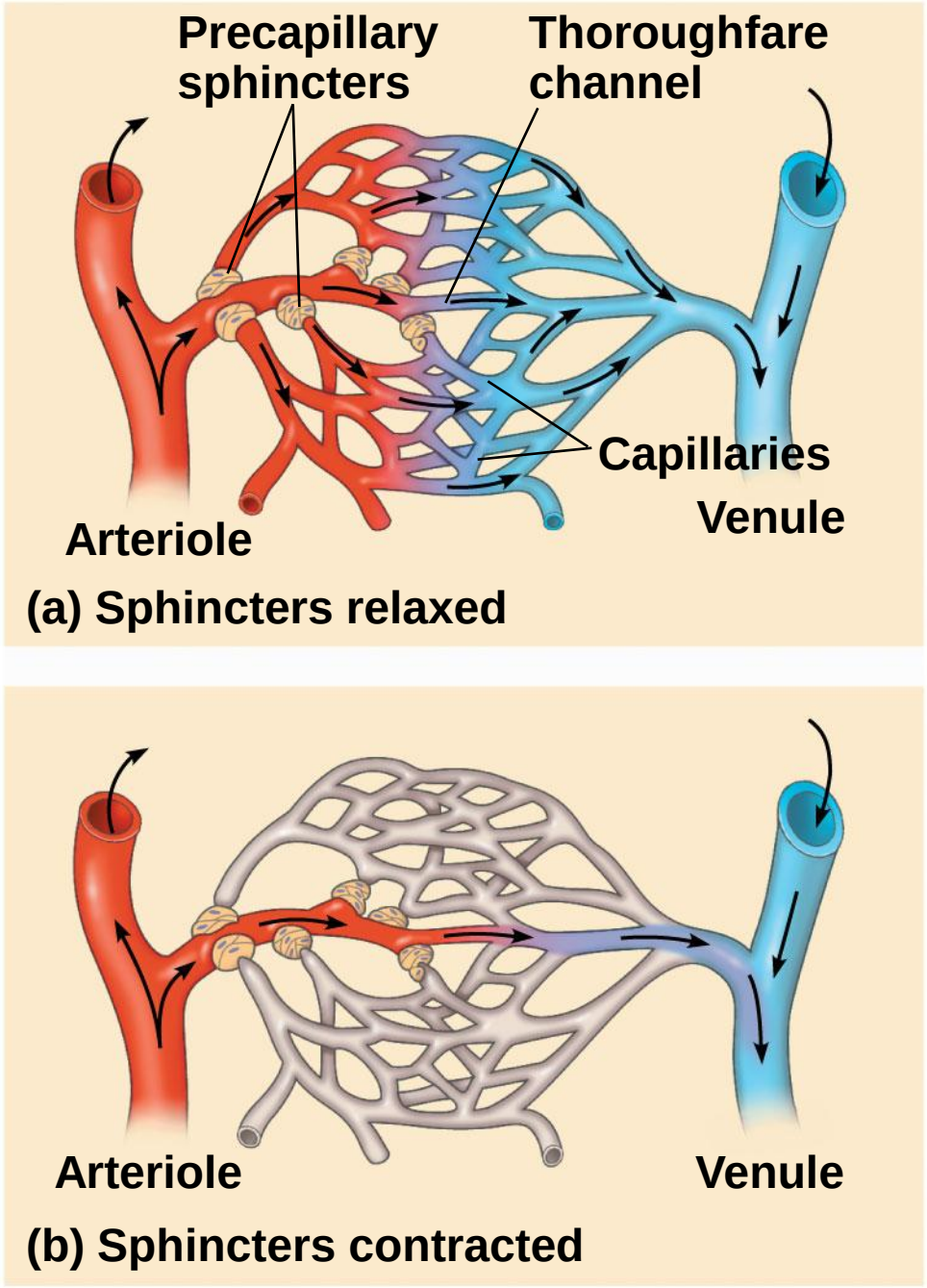


Capillary Function

- Blood flows through only 5–10% of the body's capillaries at a time
- Capillaries in major organs are usually filled to capacity
- Blood supply varies in many other sites

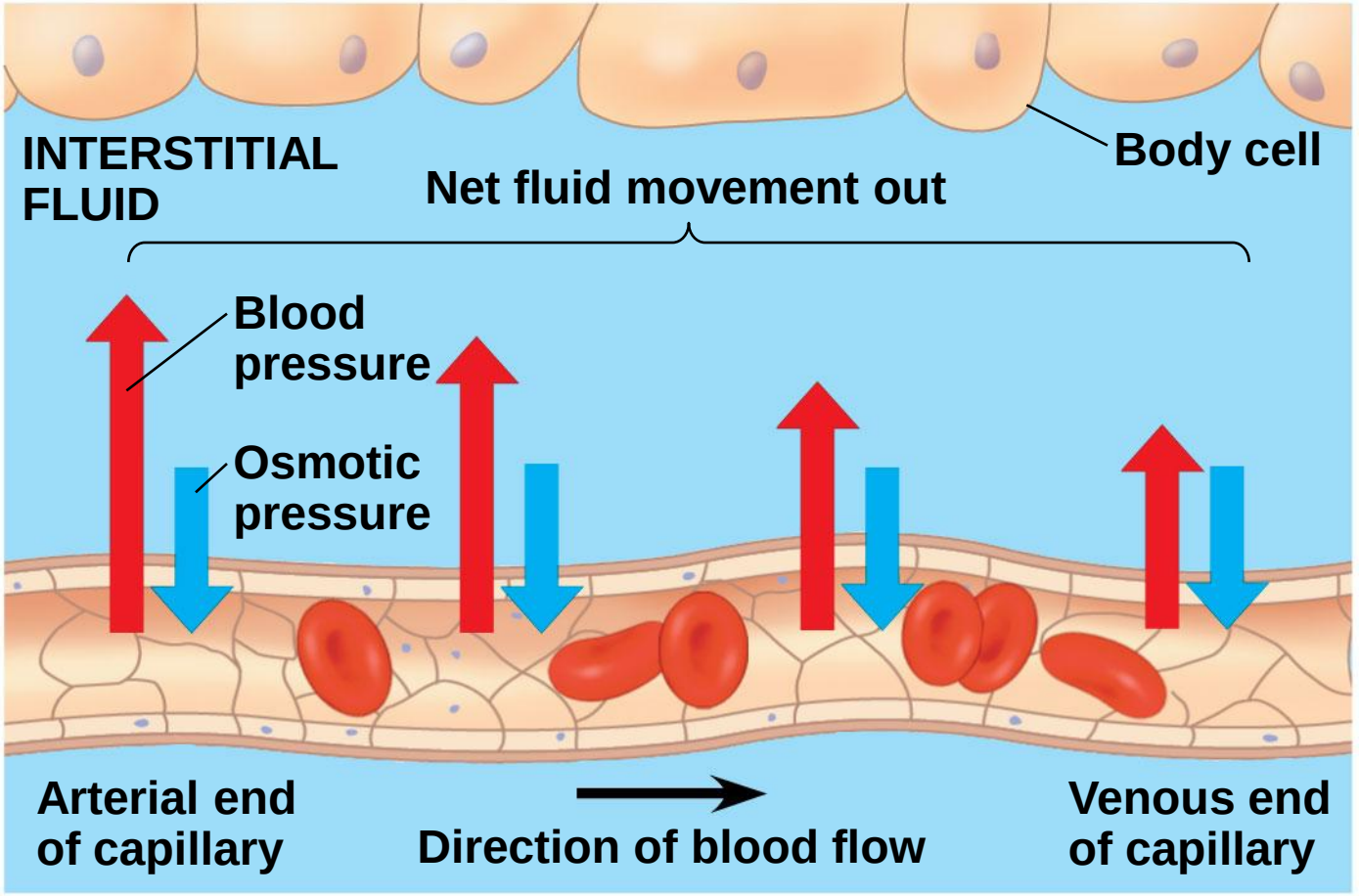
- Two mechanisms regulate distribution of blood in capillary beds
  - Contraction of the smooth muscle layer in the wall of an arteriole constricts the vessel
  - Precapillary sphincters control flow of blood between arterioles and venules
- Blood flow is regulated by nerve impulses, hormones, and other chemicals

Figure 42.14



- The exchange of substances between the blood and interstitial fluid takes place across the thin endothelial walls of the capillaries
- The difference between blood pressure and osmotic pressure drives fluids out of capillaries at the arteriole end and into capillaries at the venule end
- Most blood proteins and all blood cells are too large to pass through the endothelium

Figure 42.15



Fluid Return by the Lymphatic System

- The **lymphatic system** returns fluid that leaks out from the capillary beds
- Fluid, called **lymph**, reenters the circulation directly at the venous end of the capillary bed and indirectly through the lymphatic system
- The lymphatic system drains into veins in the neck
- Valves in lymph vessels prevent the backflow of fluid

- **Lymph nodes** are organs that filter lymph and play an important role in the body's defense
- Edema is swelling caused by disruptions in the flow of lymph

Concept 42.4: Blood components contribute to exchange, transport, and defense

- With open circulation, the fluid that is pumped comes into direct contact with all cells
- The closed circulatory systems of vertebrates contain blood, a specialized connective tissue

Blood Composition and Function

- Blood consists of several kinds of cells suspended in a liquid matrix called **plasma**
- The cellular elements occupy about 45% of the volume of blood

Figure 42.17a

Plasma 55%	
Constituent	**Major functions**
Water	Solvent for carrying other substances
Ions (blood electrolytes) Sodium Potassium Calcium Magnesium Chloride Bicarbonate	Osmotic balance, pH buffering, and regulation of membrane permeablity
Plasma proteins Albumin Fibrinogen Immunoglobulins (antibodies)	Osmotic balance, pH buffering Clotting Defense
Substances transported by blood Nutrients Waste products Respiratory gases Hormones	

Separated blood elements

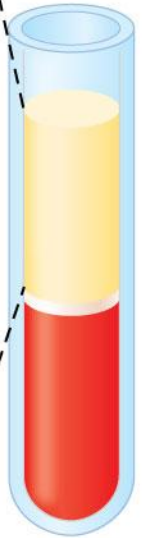
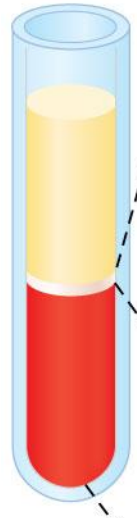


Figure 42.17b



Cellular elements 45%		
Cell type	**Number per μL (mm^3) of blood**	**Functions**
Leukocytes (white blood cells) Basophils Lymphocytes Eosinophils Neutrophils Monocytes	**5,000–10,000**	**Defense and immunity**
Platelets	**250,000–400,000**	**Blood clotting**
Erythrocytes (red blood cells)	**5–6 million**	**Transport of O_2 and some CO_2**

Cardiovascular Disease

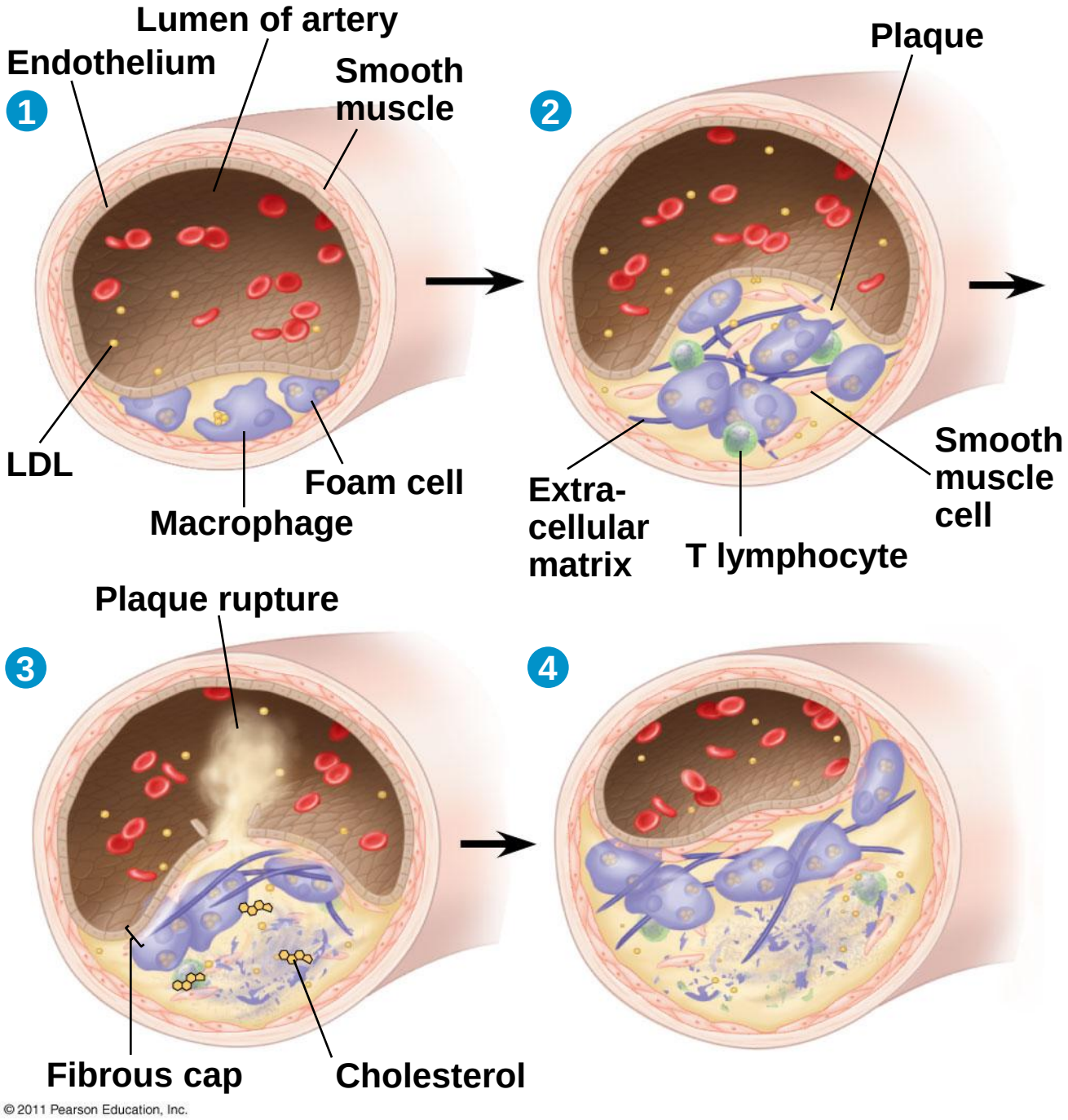
- Cardiovascular diseases are disorders of the heart and the blood vessels
- Cardiovascular diseases account for more than half the deaths in the United States
- Cholesterol, a steroid, helps maintain membrane fluidity

- **Low-density lipoprotein (LDL)** delivers cholesterol to cells for membrane production
- **High-density lipoprotein (HDL)** scavenges cholesterol for return to the liver
- Risk for heart disease increases with a high LDL to HDL ratio
- Inflammation is also a factor in cardiovascular disease

Atherosclerosis, Heart Attacks, and Stroke

- One type of cardiovascular disease, **atherosclerosis**, is caused by the buildup of plaque deposits within arteries

Figure 42.20



- A **heart attack,** or myocardial infarction, is the death of cardiac muscle tissue resulting from blockage of one or more coronary arteries
- Coronary arteries supply oxygen-rich blood to the heart muscle
- A **stroke** is the death of nervous tissue in the brain, usually resulting from rupture or blockage of arteries in the head
- Angina pectoris is caused by partial blockage of the coronary arteries and results in chest pains

Concept 42.5: Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** supplies O_2 for cellular respiration and disposes of CO_2

Partial Pressure Gradients in Gas Exchange

- A gas diffuses from a region of higher partial pressure to a region of lower partial pressure
- **Partial pressure** is the pressure exerted by a particular gas in a mixture of gases
- Gases diffuse down pressure gradients in the lungs and other organs as a result of differences in partial pressure

Respiratory Media

- Animals can use air or water as a source of O_2, or respiratory medium
- In a given volume, there is less O_2 available in water than in air
- Obtaining O_2 from water requires greater efficiency than air breathing

Respiratory Surfaces

- Animals require large, moist respiratory surfaces for exchange of gases between their cells and the respiratory medium, either air or water
- Gas exchange across respiratory surfaces takes place by diffusion
- Respiratory surfaces vary by animal and can include the outer surface, skin, gills, tracheae, and lungs

- **Ventilation** moves the respiratory medium over the respiratory surface
- Aquatic animals move through water or move water over their gills for ventilation
- Fish gills use a **countercurrent exchange** system, where blood flows in the opposite direction to water passing over the gills; blood is always less saturated with O_2 than the water it meets

Figure 42.23

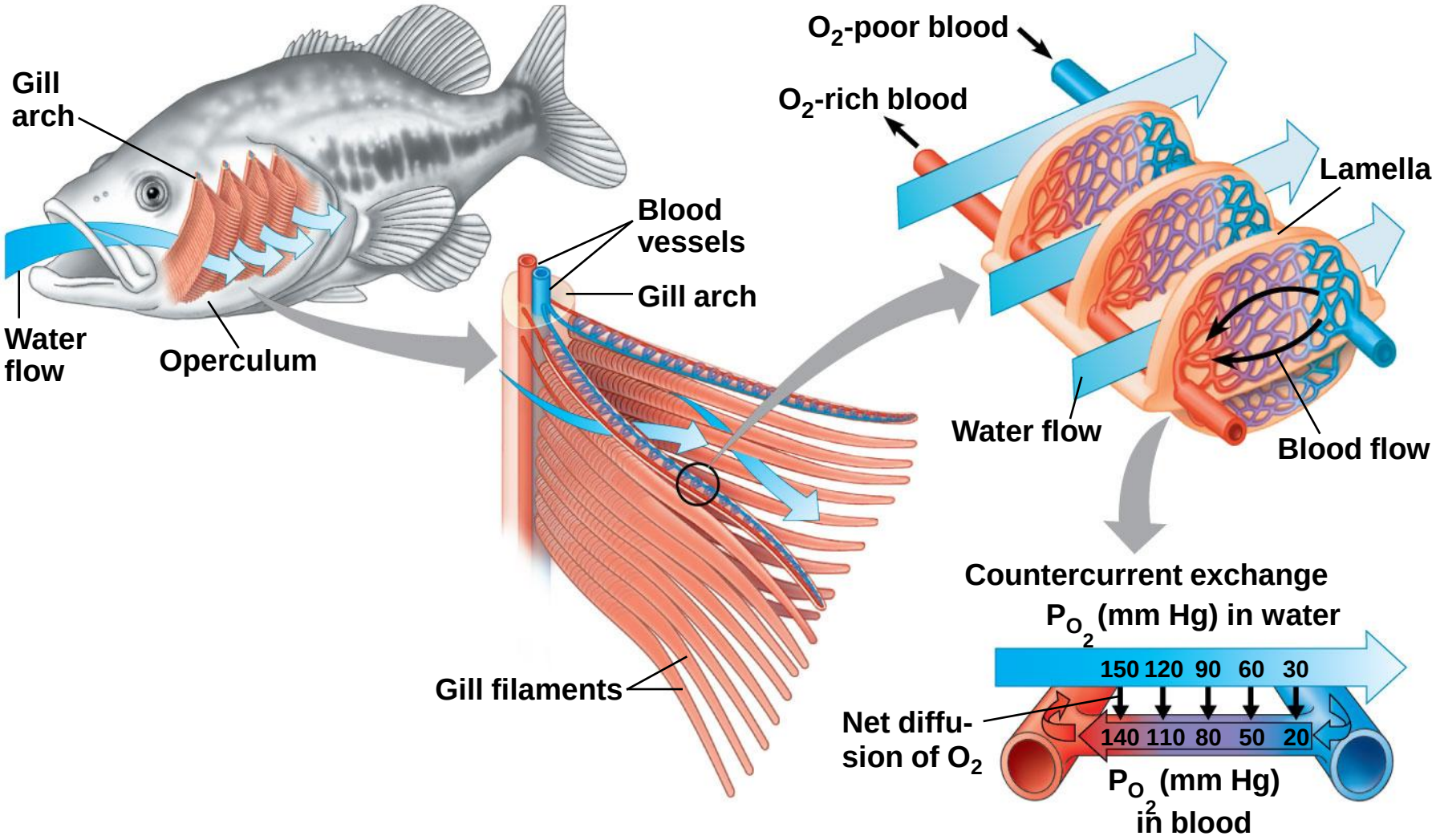


Figure 42.23a

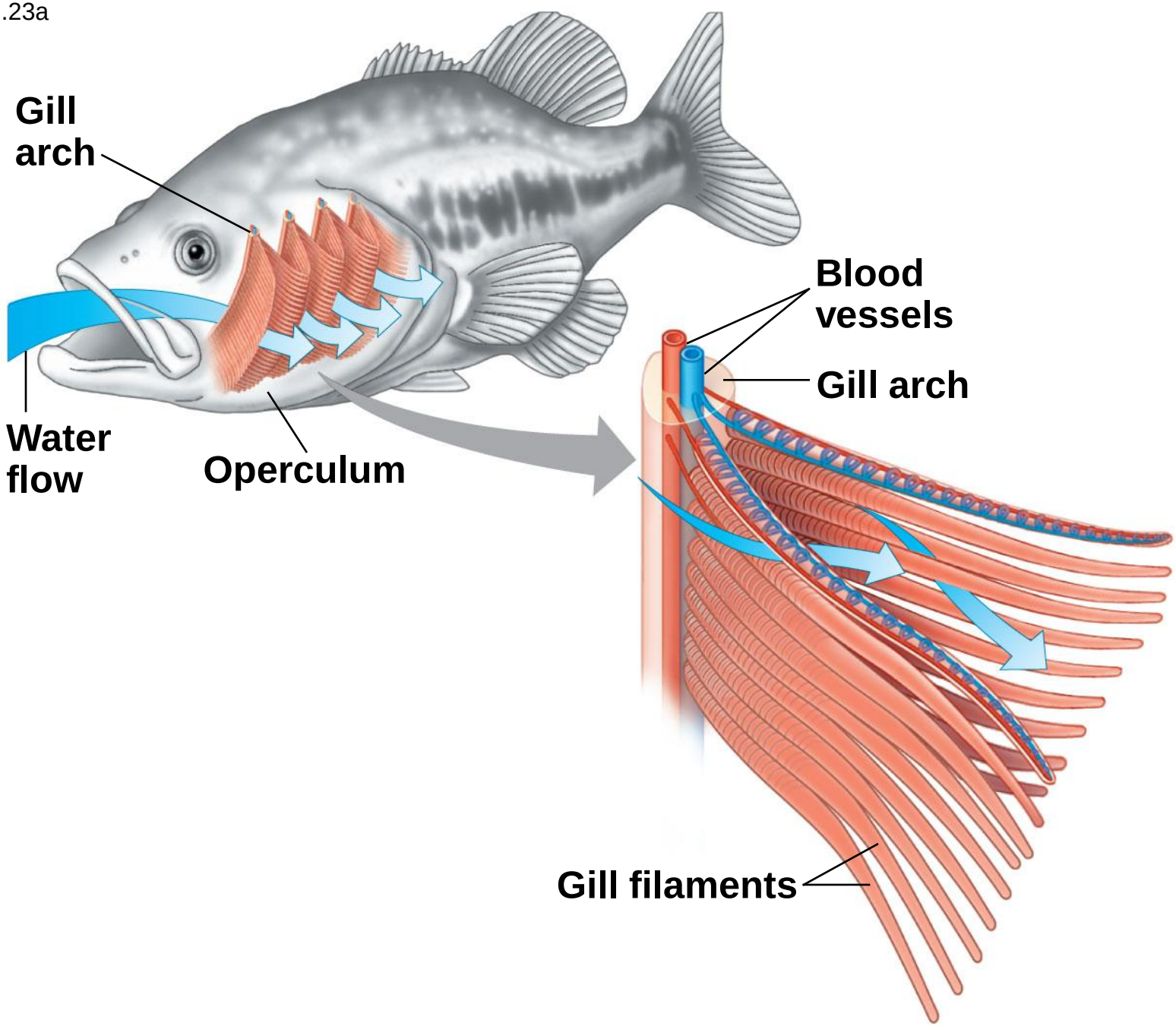
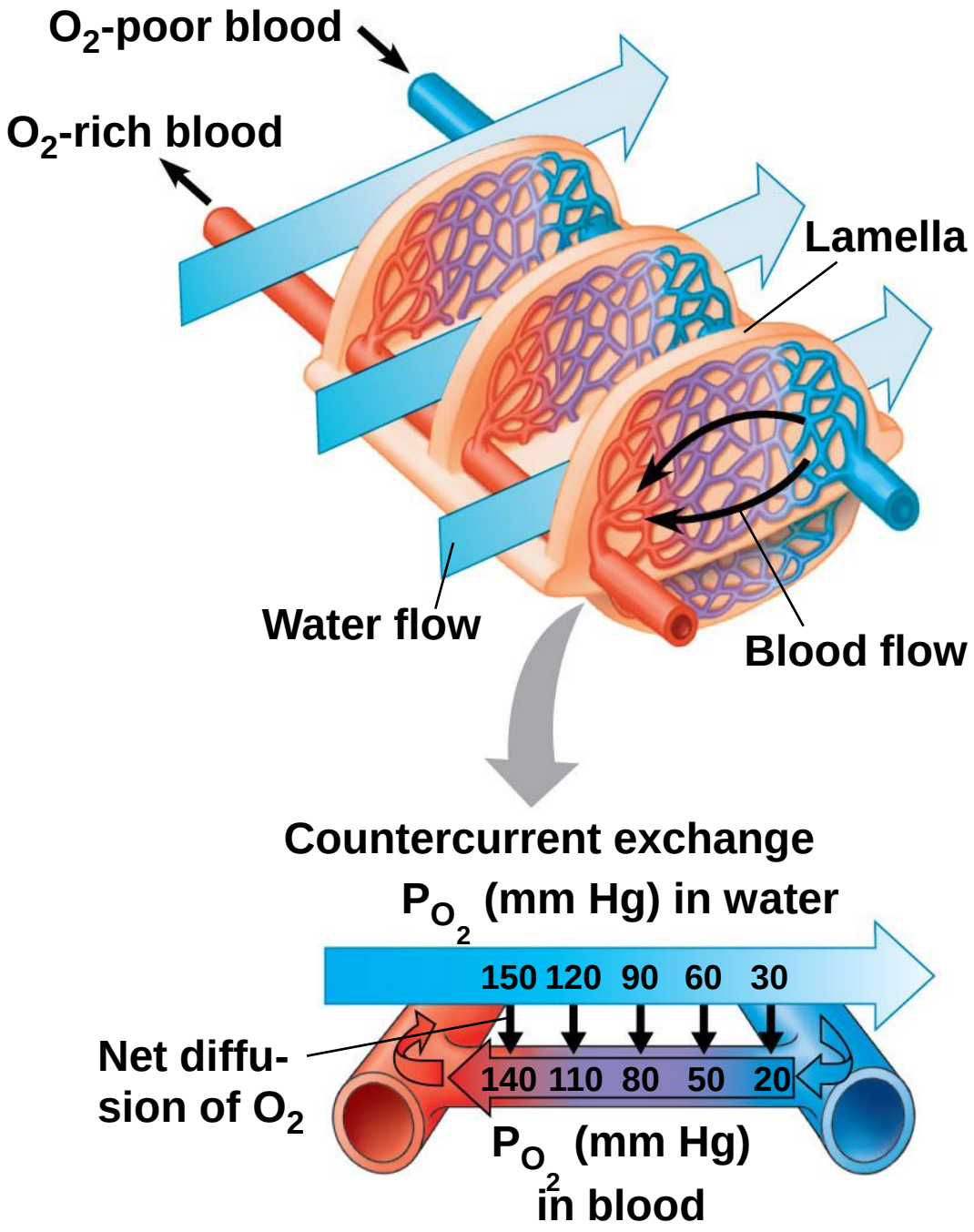


Figure 42.23b



Lungs

- **Lungs** are an infolding of the body surface
- The circulatory system (open or closed) transports gases between the lungs and the rest of the body
- The size and complexity of lungs correlate with an animal's metabolic rate

Mammalian Respiratory Systems: A Closer Look

- A system of branching ducts conveys air to the lungs
- Air inhaled through the nostrils is warmed, humidified, and sampled for odors
- The pharynx directs air to the lungs and food to the stomach
- Swallowing tips the epiglottis over the glottis in the pharynx to prevent food from entering the **trachea**

Figure 42.25

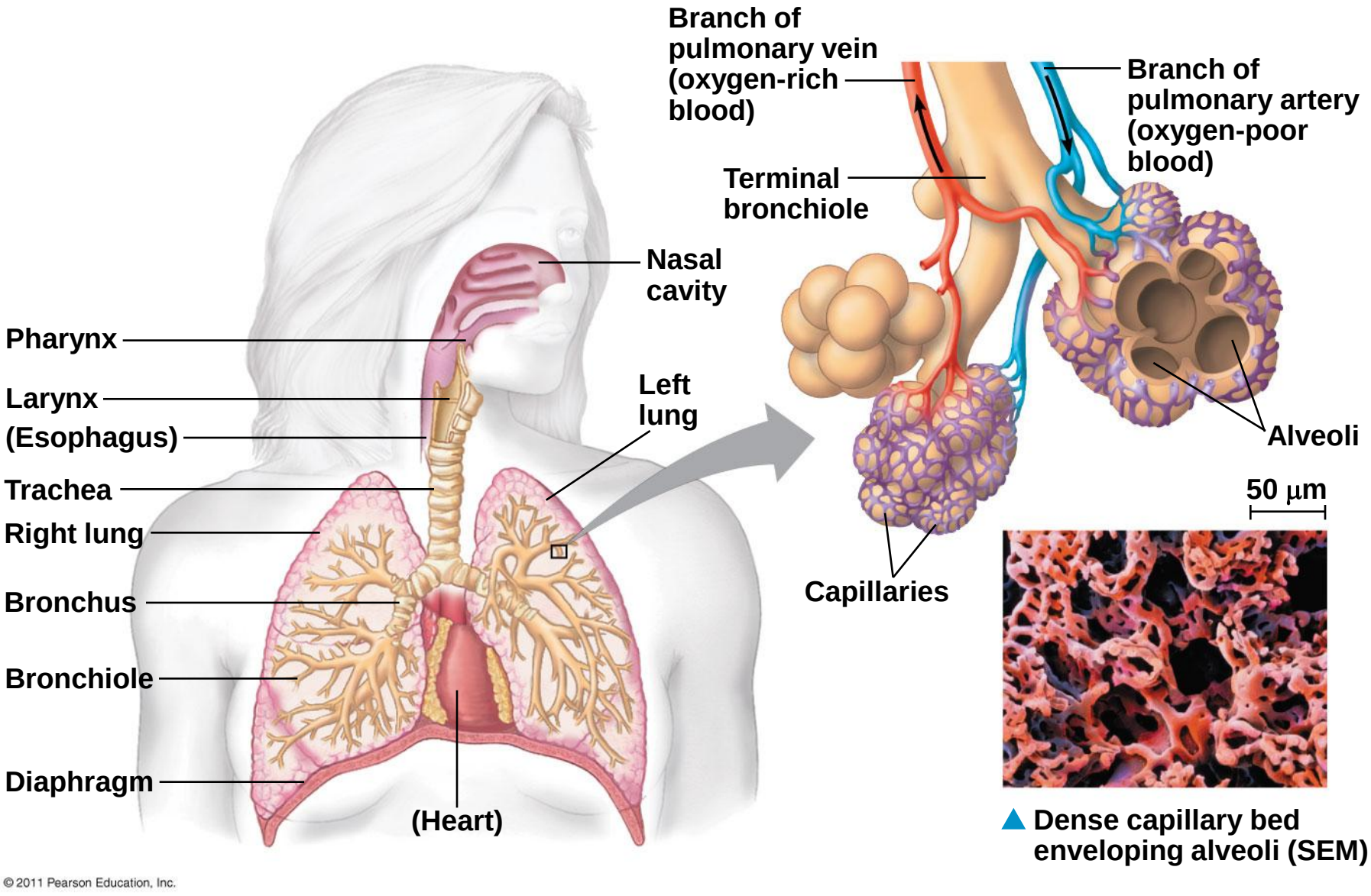


Figure 42.25a

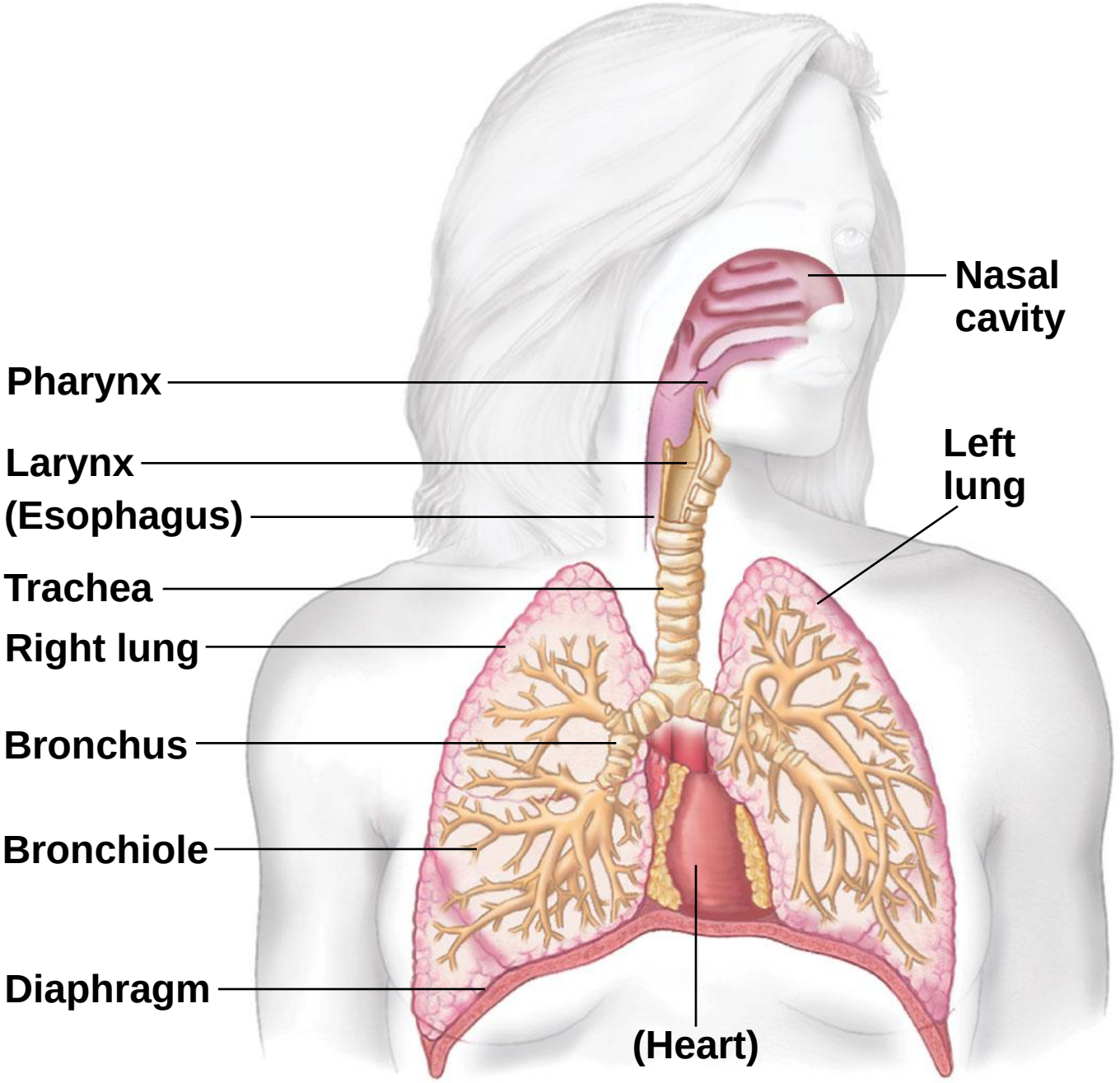


Figure 42.25b

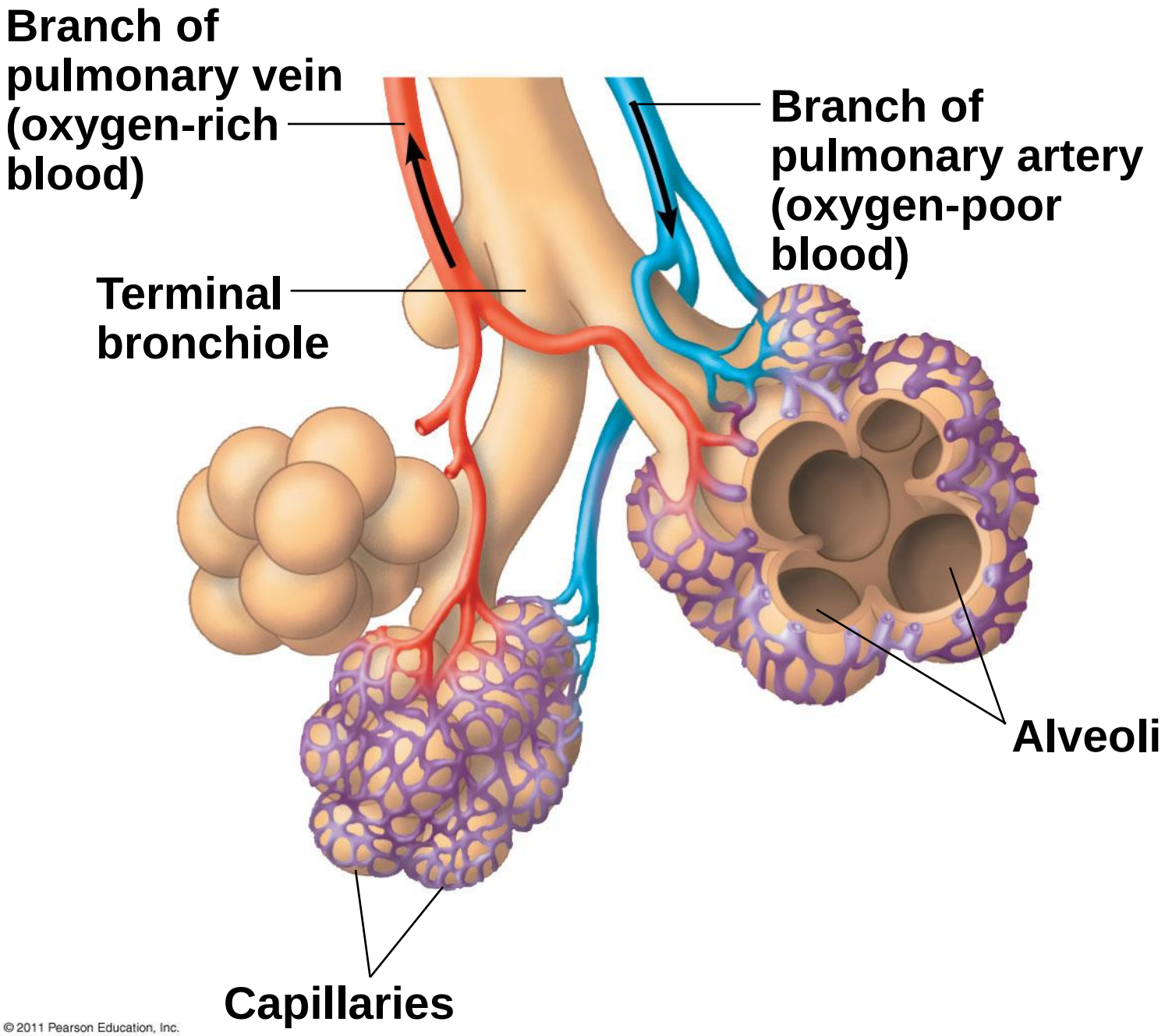
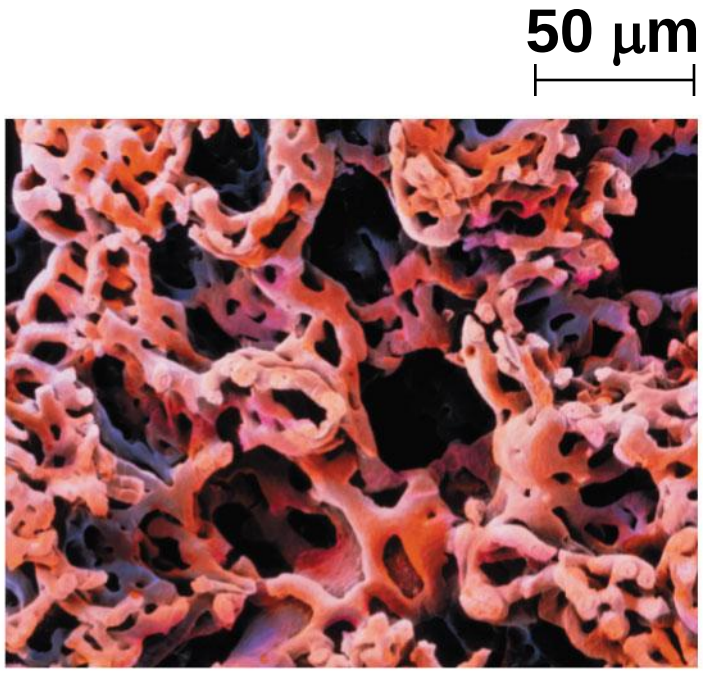


Figure 42.25c



▲ **Dense capillary bed enveloping alveoli (SEM)**

- Air passes through the pharynx, **larynx**, trachea, **bronchi**, and **bronchioles** to the alveoli, where gas exchange occurs
- Exhaled air passes over the vocal cords in the larynx to create sounds
- Cilia and mucus line the epithelium of the air ducts and move particles up to the pharynx
- This “mucus escalator” cleans the respiratory system and allows particles to be swallowed into the esophagus

- Gas exchange takes place in **alveoli**, air sacs at the tips of bronchioles
- Oxygen diffuses through the moist film of the epithelium and into capillaries
- Carbon dioxide diffuses from the capillaries across the epithelium and into the air space

- Alveoli lack cilia and are susceptible to contamination
- Secretions called **surfactants** coat the surface of the alveoli
- Preterm babies lack surfactant and are vulnerable to respiratory distress syndrome; treatment is provided by artificial surfactants

Concept 42.6: Breathing ventilates the lungs

- The process that ventilates the lungs is **breathing**, the alternate inhalation and exhalation of air

How an Amphibian Breathes

- An amphibian such as a frog ventilates its lungs by **positive pressure breathing**, which forces air down the trachea

How a Bird Breathes

- Birds have eight or nine air sacs that function as bellows that keep air flowing through the lungs
- Air passes through the lungs in one direction only
- Every exhalation completely renews the air in the lungs

Figure 42.27

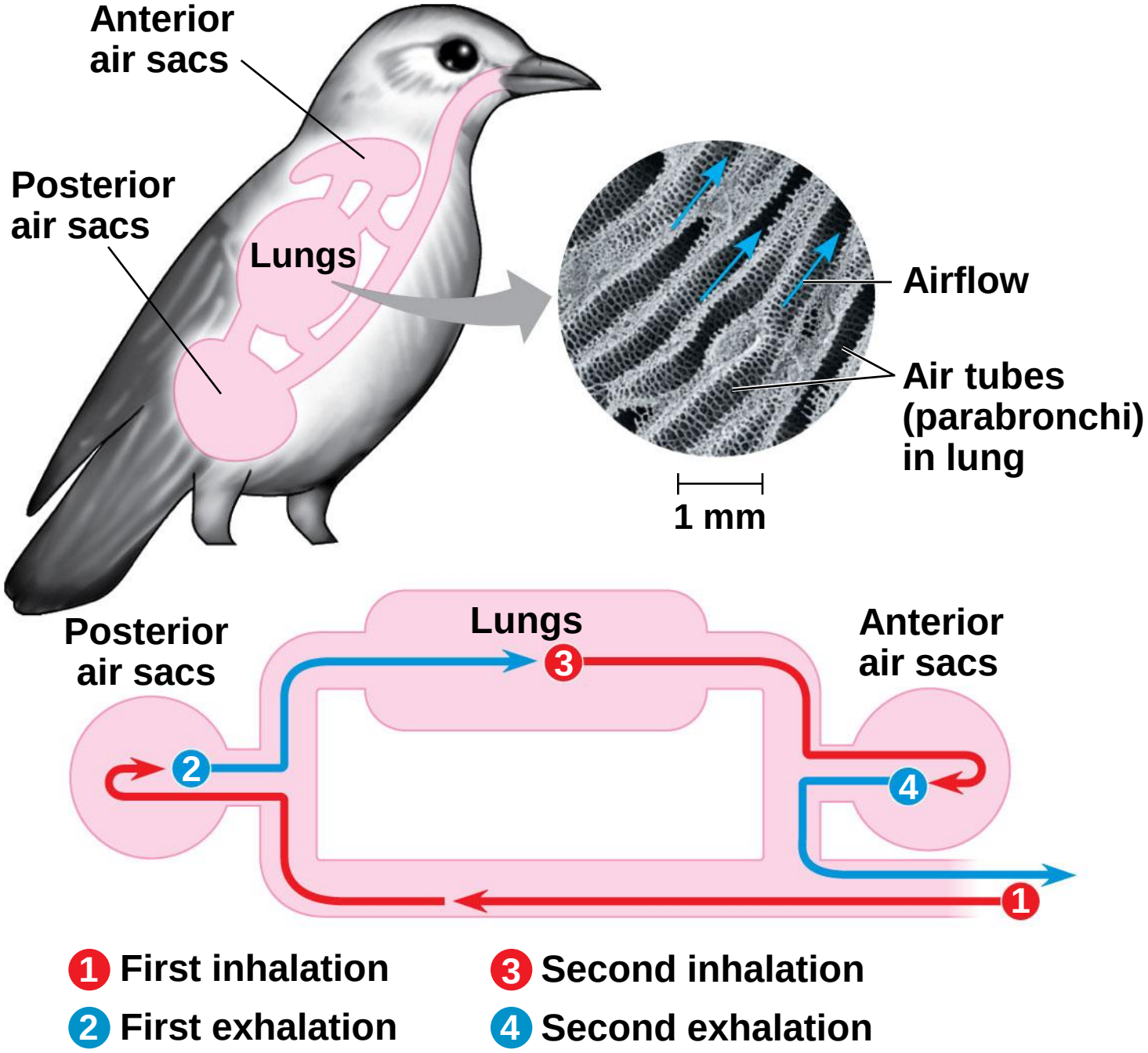
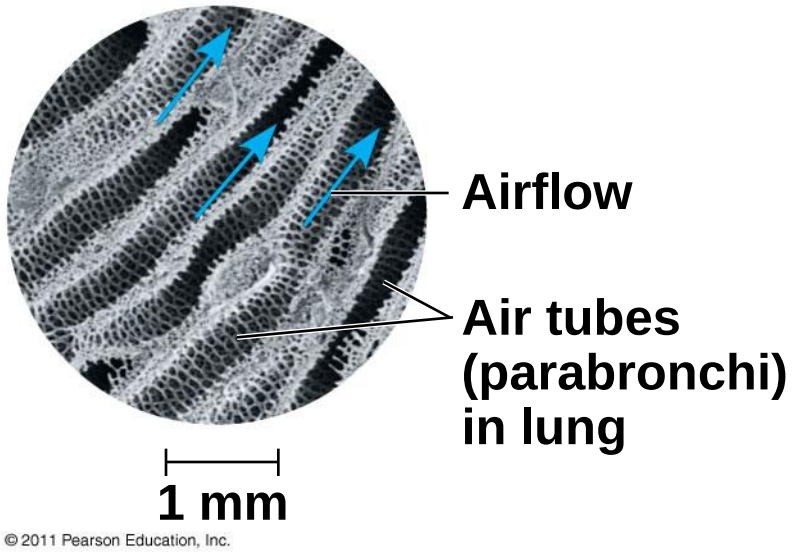


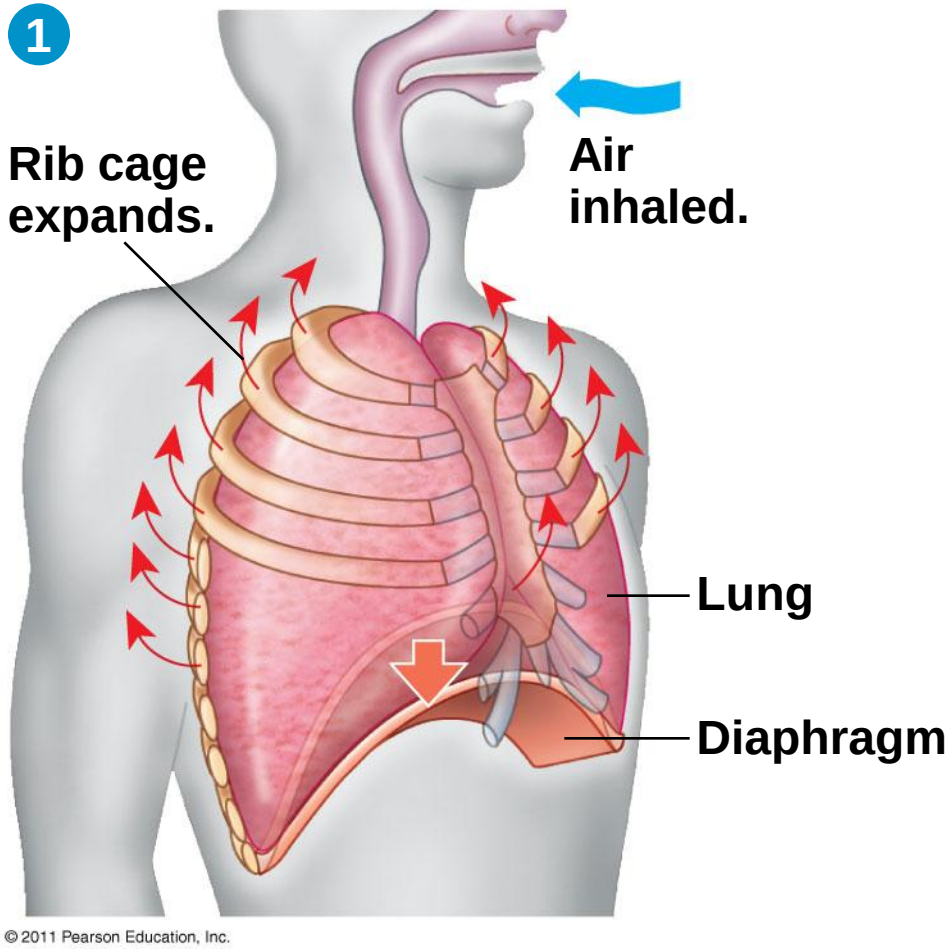
Figure 42.27a



How a Mammal Breathes

- Mammals ventilate their lungs by **negative pressure breathing**, which pulls air into the lungs
- Lung volume increases as the rib muscles and **diaphragm** contract
- The **tidal volume** is the volume of air inhaled with each breath

Figure 42.28



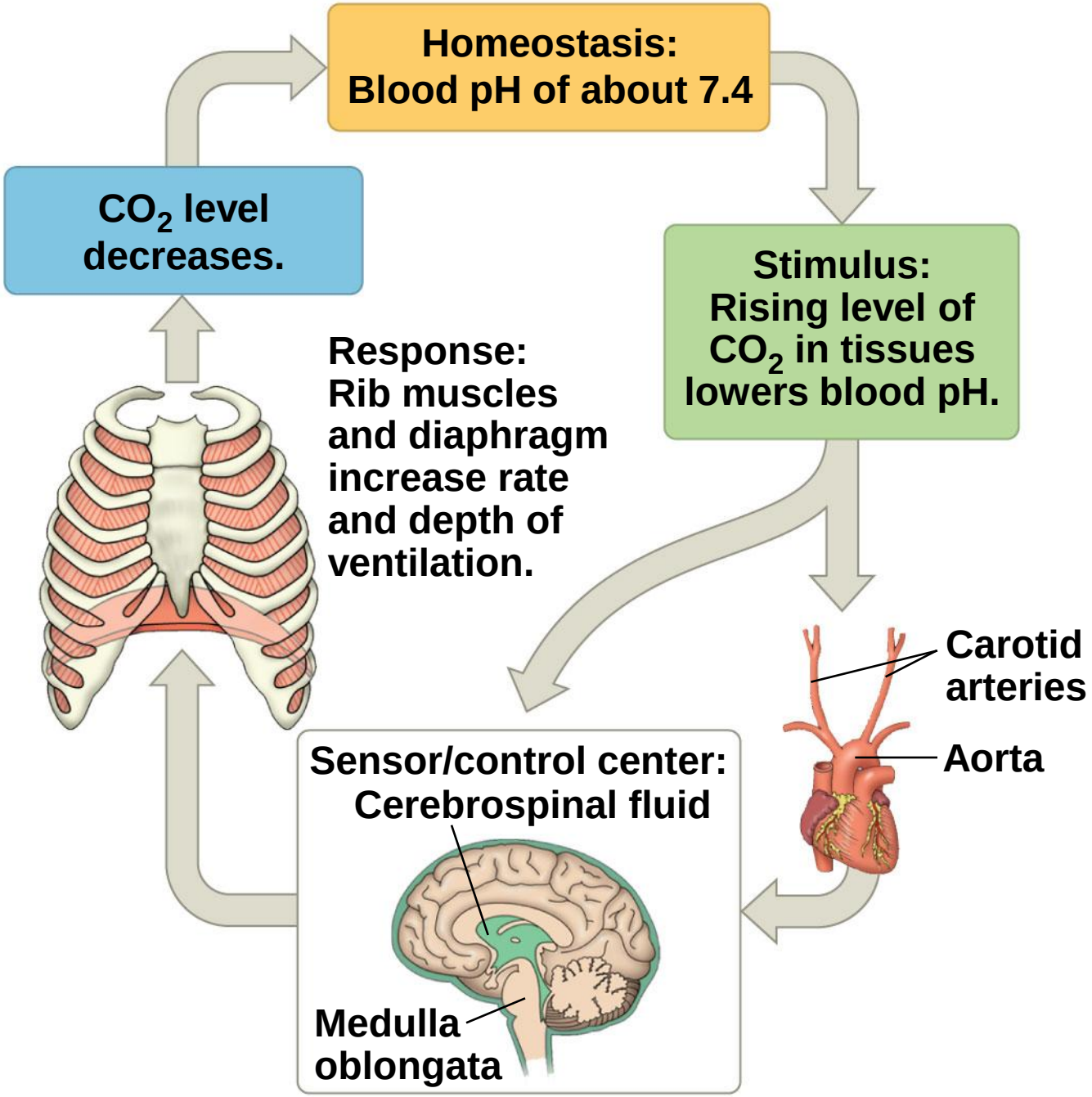
- The maximum tidal volume is the **vital capacity**
- After exhalation, a **residual volume** of air remains in the lungs

Control of Breathing in Humans

- In humans, the main **breathing control centers** are in two regions of the brain, the medulla oblongata and the pons
- The medulla regulates the rate and depth of breathing in response to pH changes in the cerebrospinal fluid
- The medulla adjusts breathing rate and depth to match metabolic demands
- The pons regulates the tempo

- Sensors in the aorta and carotid arteries monitor O_2 and CO_2 concentrations in the blood
- These sensors exert secondary control over breathing

Figure 42.29



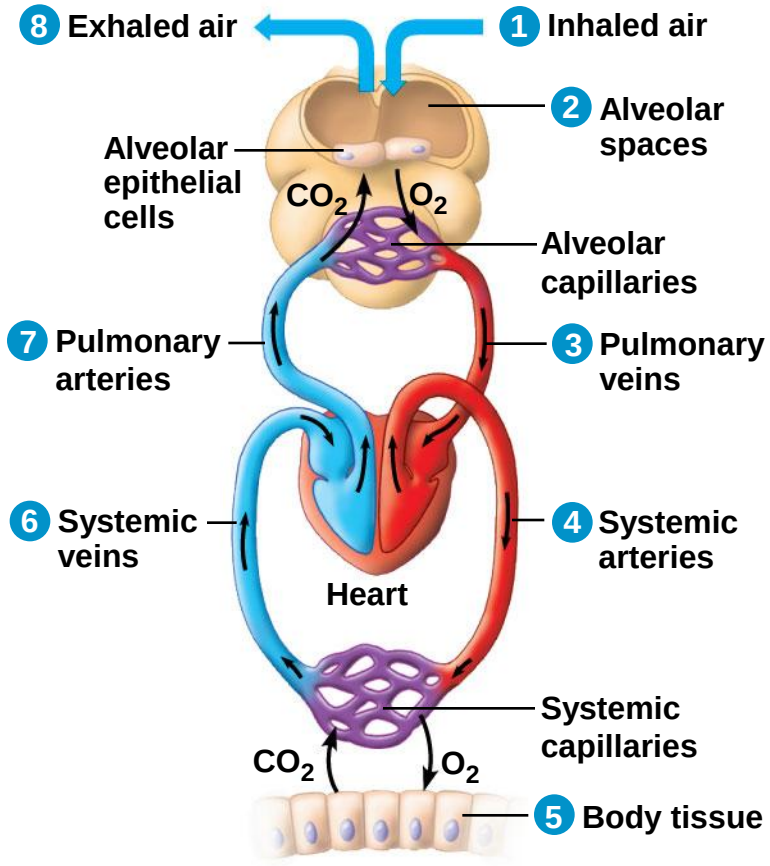
Concept 42.7: Adaptations for gas exchange include pigments that bind and transport gases

- The metabolic demands of many organisms require that the blood transport large quantities of O_2 and CO_2

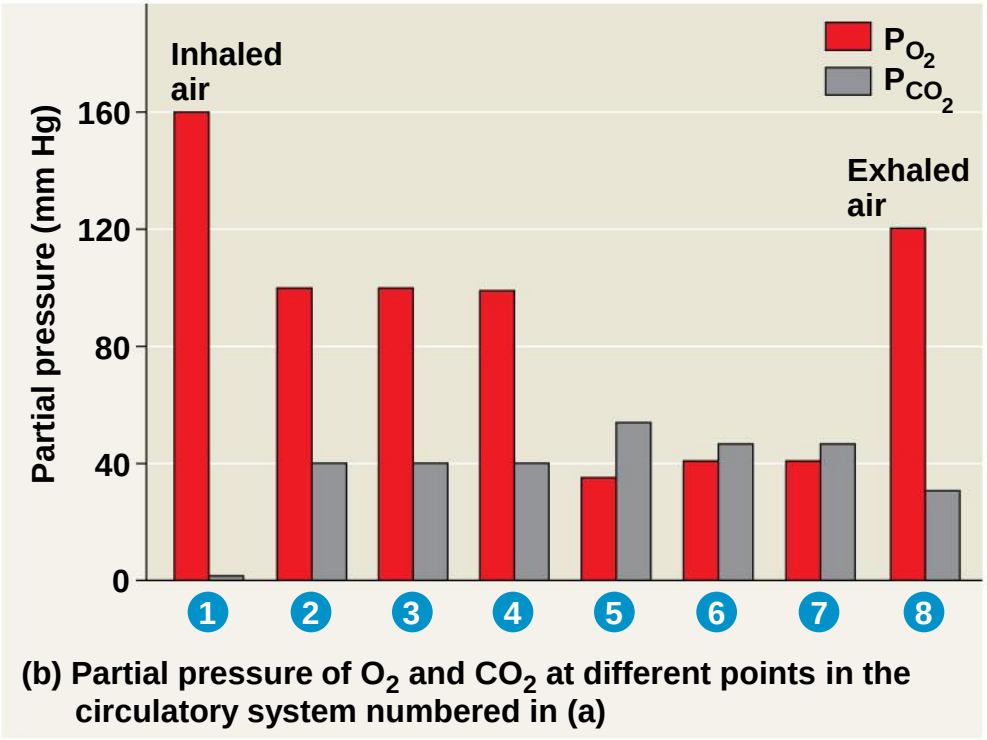
Coordination of Circulation and Gas Exchange

- Blood arriving in the lungs has a low partial pressure of O_2 and a high partial pressure of CO_2 relative to air in the alveoli
- In the alveoli, O_2 diffuses into the blood and CO_2 diffuses into the air
- In tissue capillaries, partial pressure gradients favor diffusion of O_2 into the interstitial fluids and CO_2 into the blood

Figure 42.30

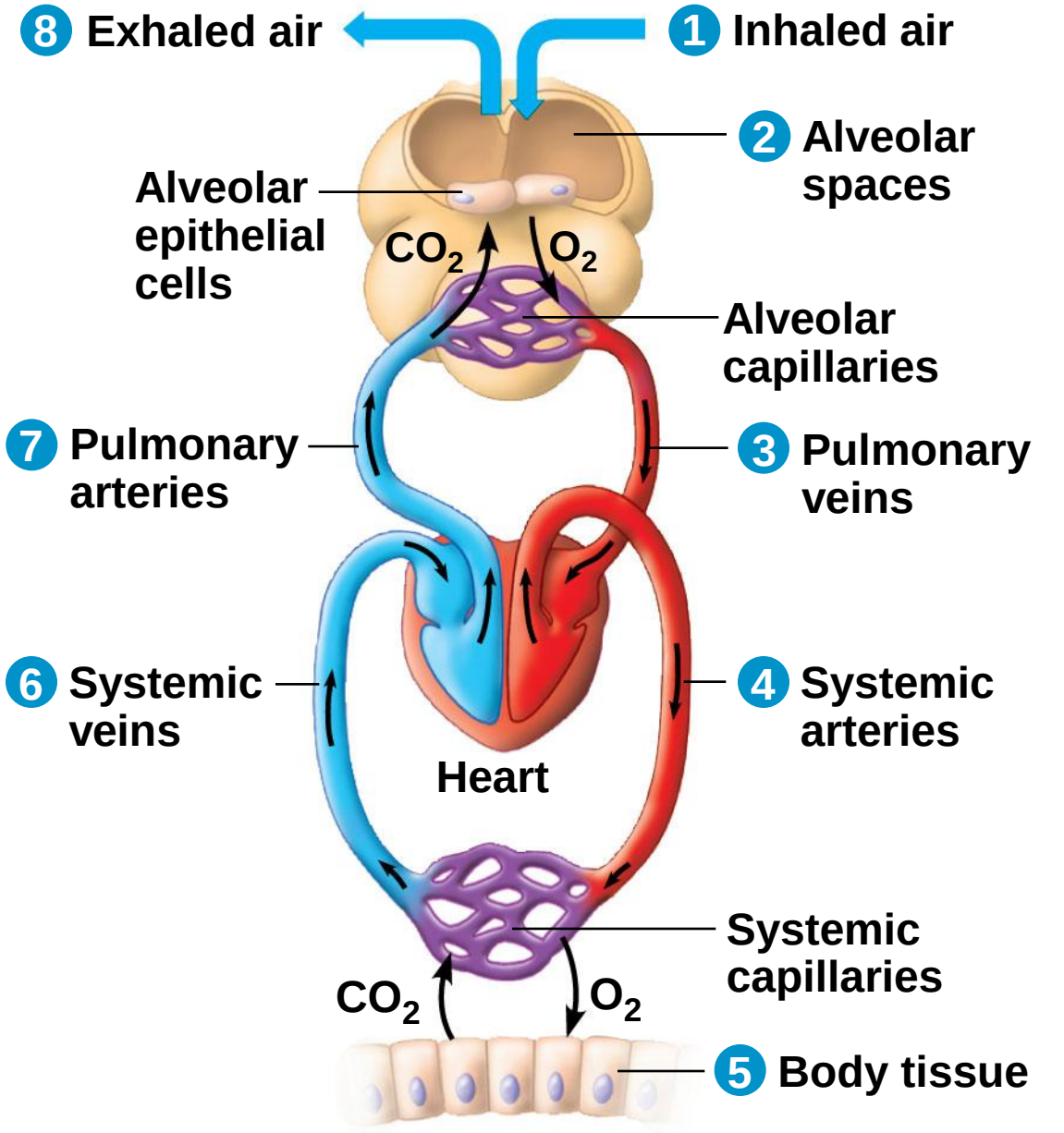


(a) The path of respiratory gases in the circulatory system



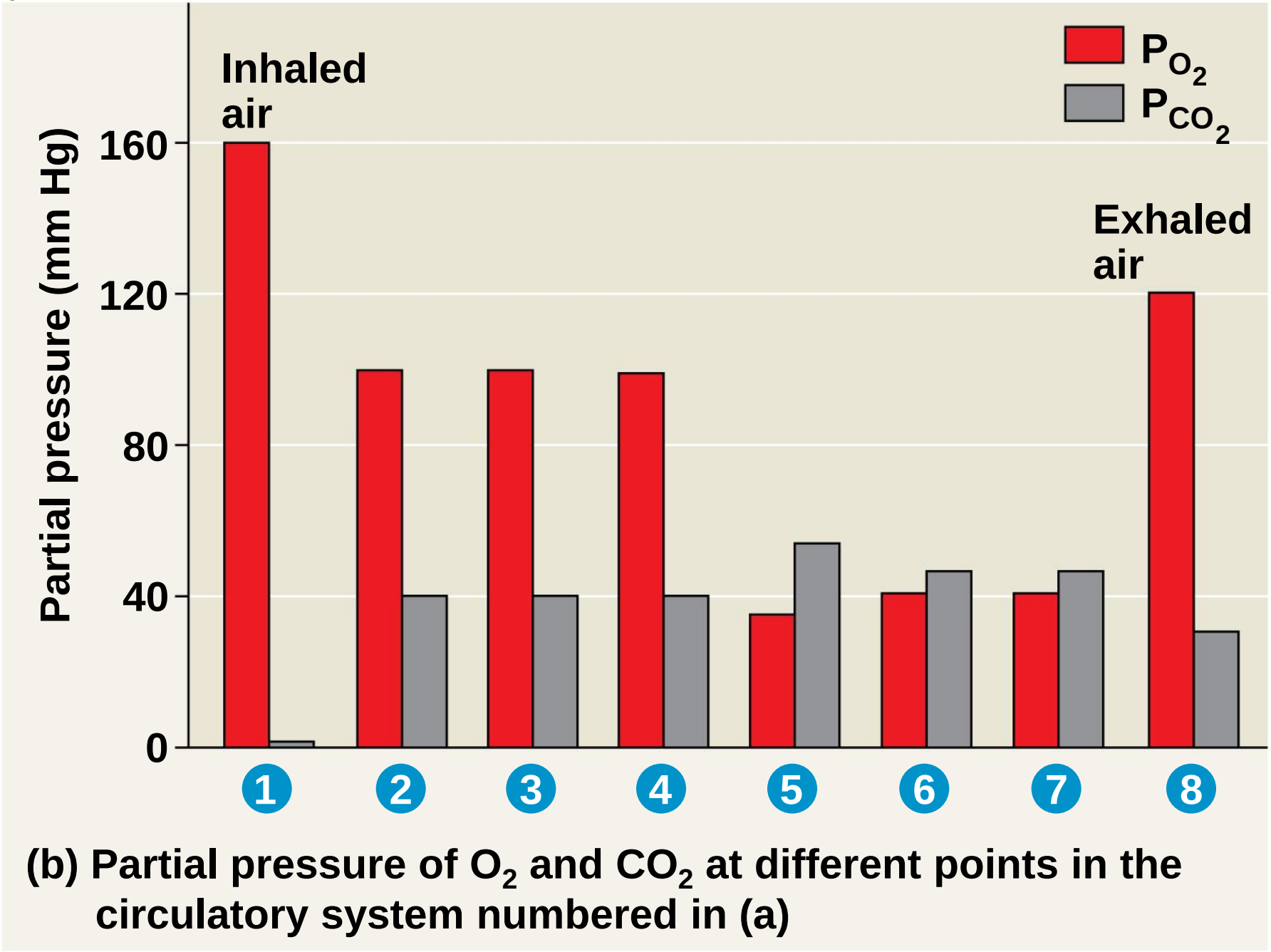
(b) Partial pressure of O_2 and CO_2 at different points in the circulatory system numbered in (a)

Figure 42.30a



(a) The path of respiratory gases in the circulatory system

Figure 42.30b



(b) Partial pressure of O_2 and CO_2 at different points in the circulatory system numbered in (a)

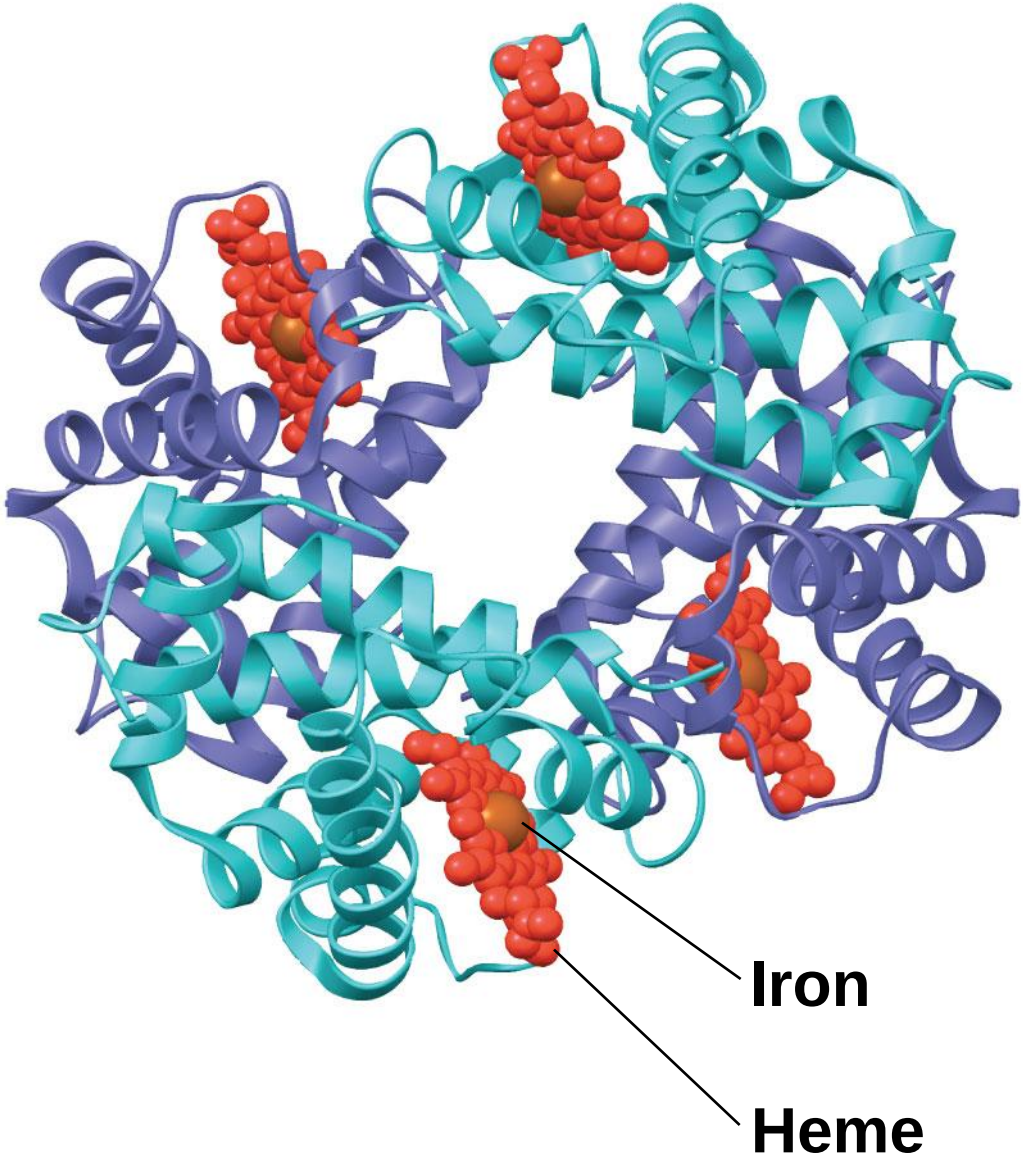
Respiratory Pigments

- **Respiratory pigments**, proteins that transport oxygen, greatly increase the amount of oxygen that blood can carry
- Arthropods and many molluscs have hemocyanin with copper as the oxygen-binding component
- Most vertebrates and some invertebrates use hemoglobin
- In vertebrates, hemoglobin is contained within erythrocytes

Hemoglobin

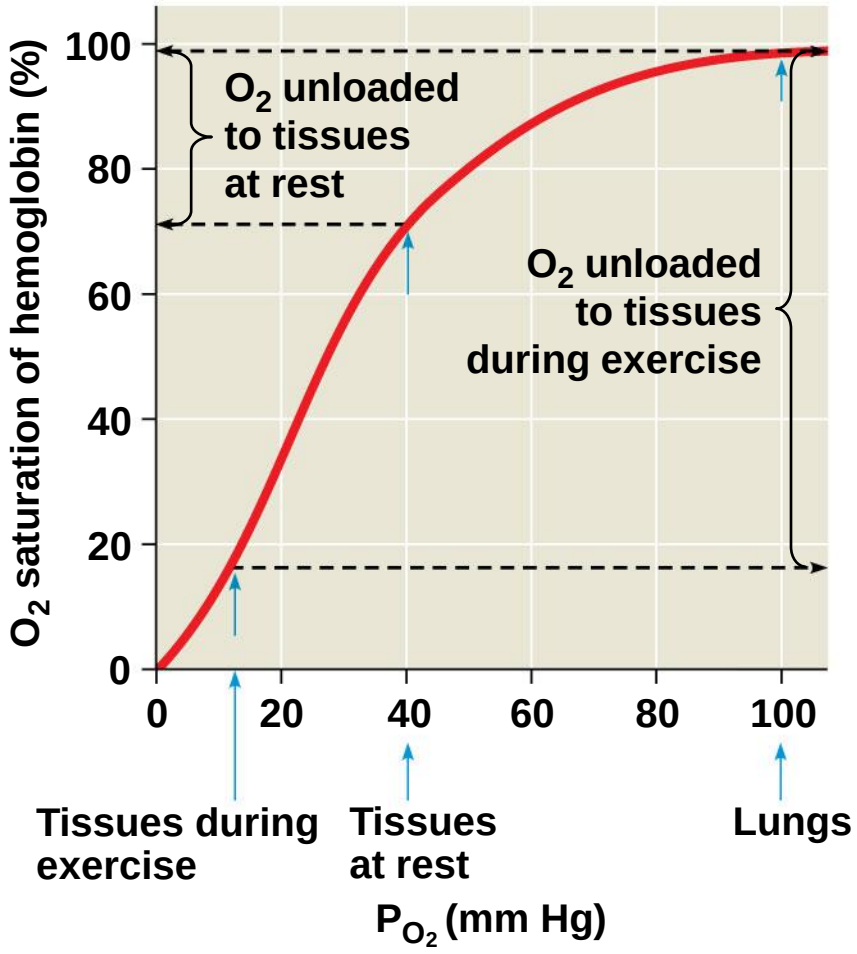
- A single hemoglobin molecule can carry four molecules of O_2, one molecule for each iron-containing heme group
- The hemoglobin dissociation curve shows that a small change in the partial pressure of oxygen can result in a large change in delivery of O_2
- CO_2 produced during cellular respiration lowers blood pH and decreases the affinity of hemoglobin for O_2; this is called the **Bohr shift**

Figure 42.UN01

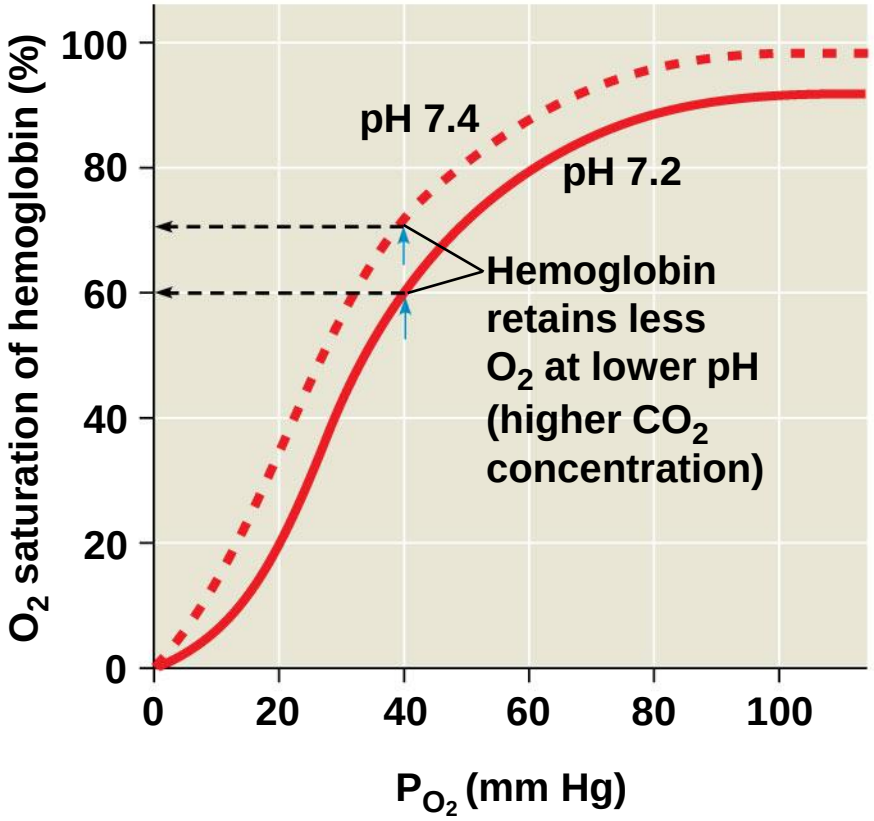


Hemoglobin

Figure 42.31

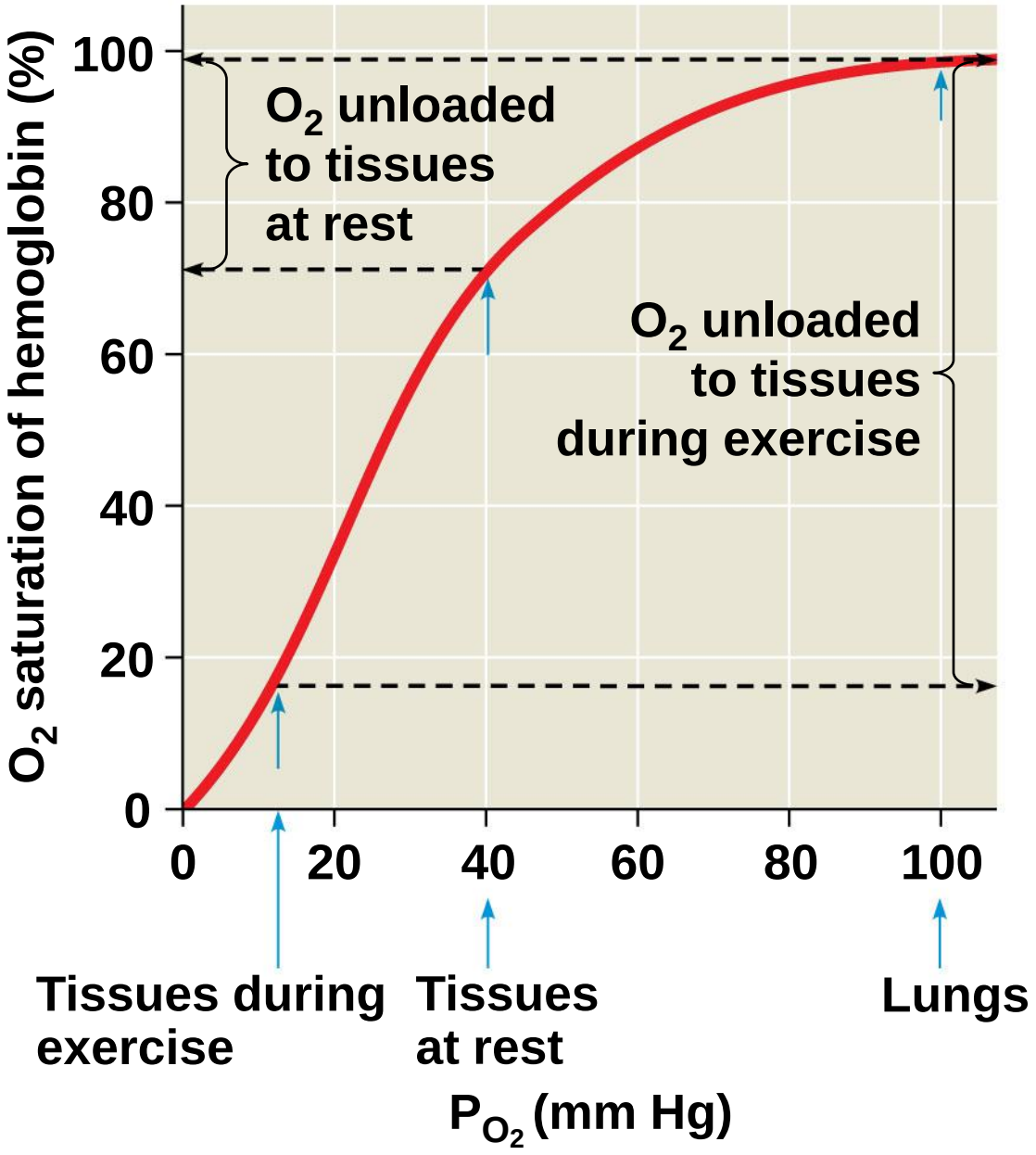


(a) P_{O_2} and hemoglobin dissociation at pH 7.4



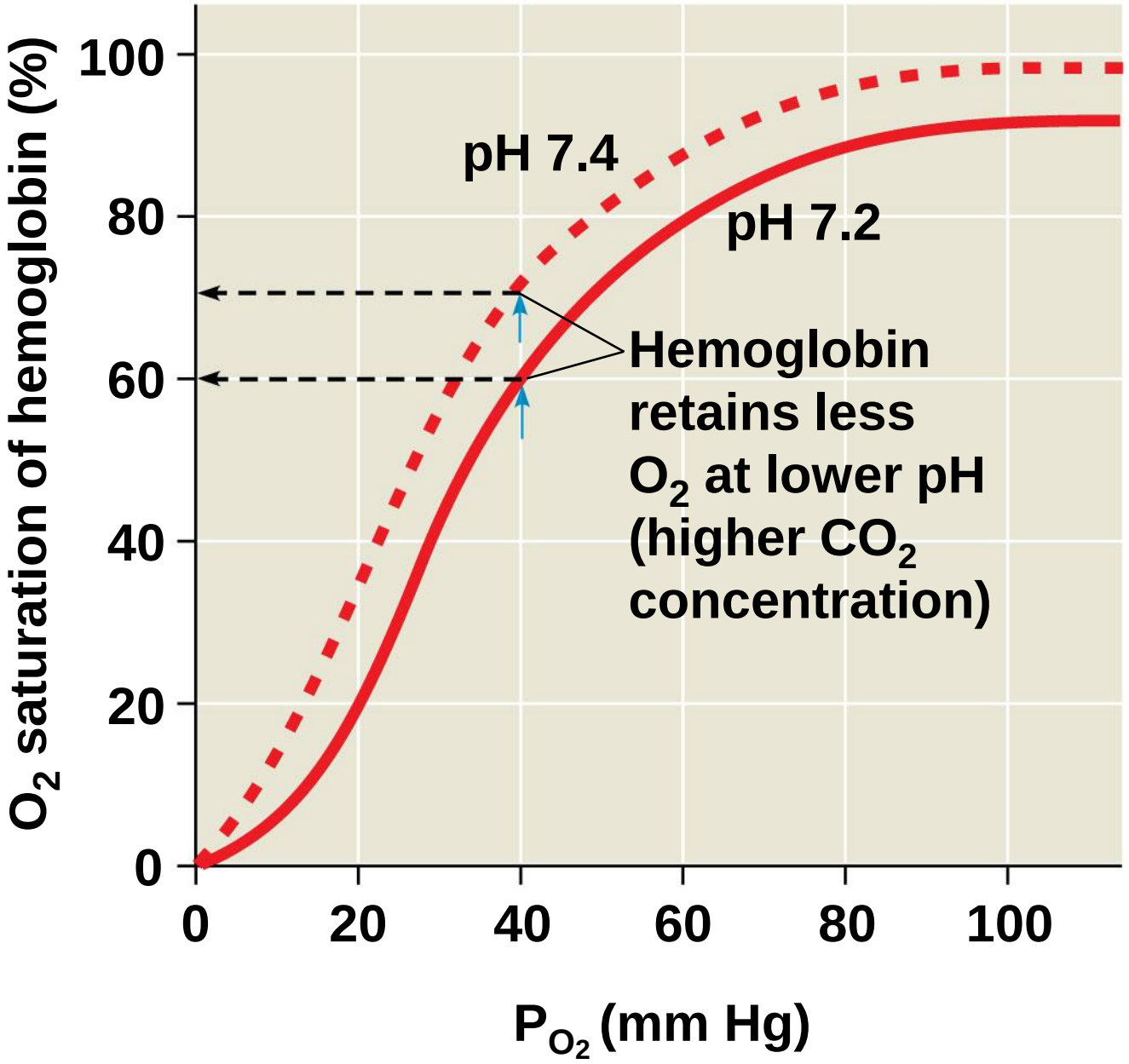
(b) pH and hemoglobin dissociation

Figure 42.31a



(a) P_{O_2} and hemoglobin dissociation at pH 7.4

Figure 42.31b



(b) pH and hemoglobin dissociation

Carbon Dioxide Transport

- Hemoglobin also helps transport CO_2 and assists in buffering the blood
- CO_2 from respiring cells diffuses into the blood and is transported in blood plasma, bound to hemoglobin, or as bicarbonate ions (HCO_3^-)

Figure 42.32

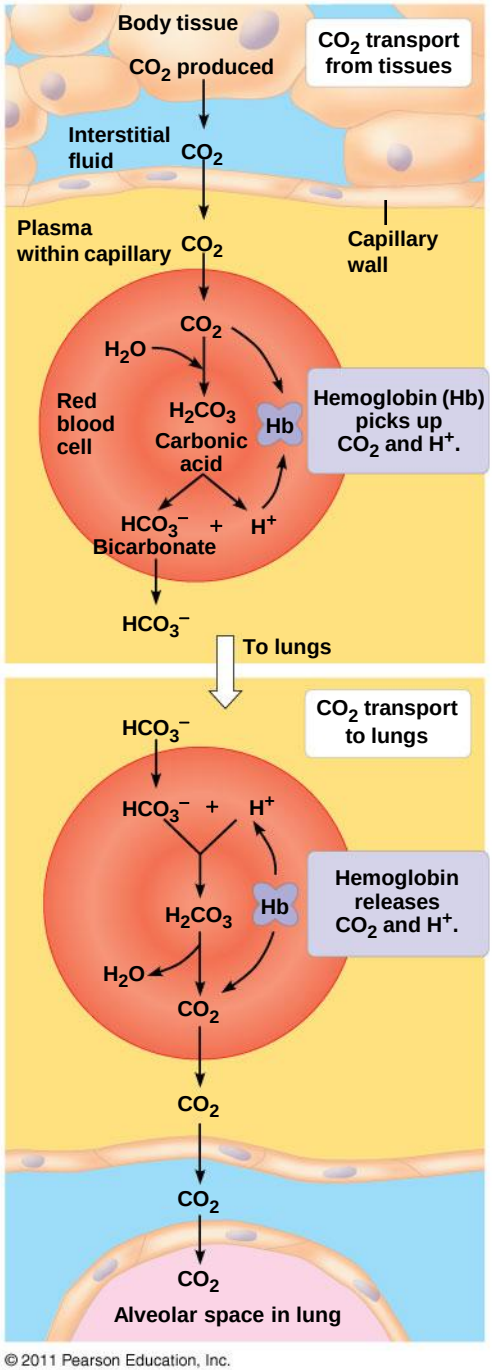


Figure 42.32a

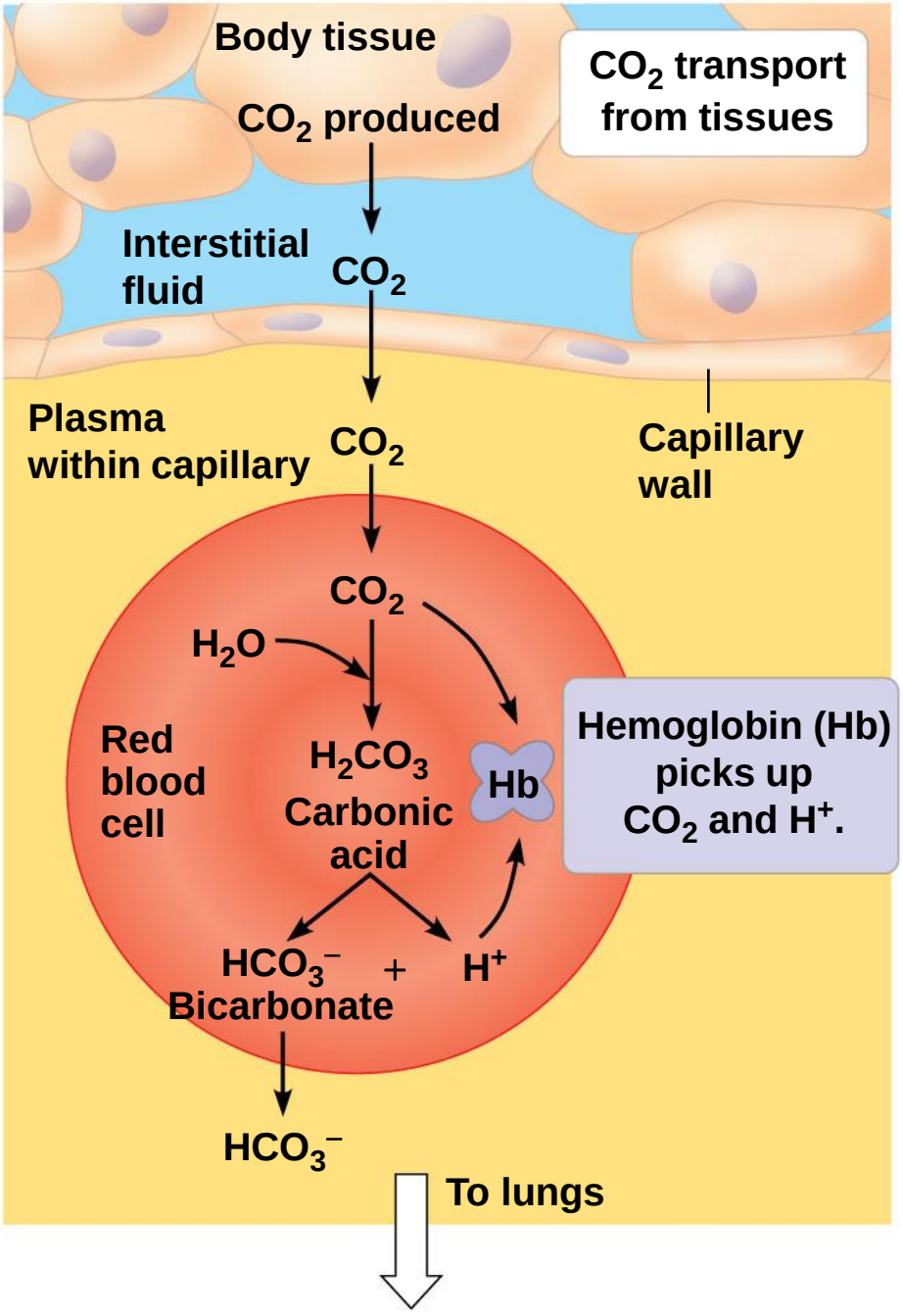


Figure 42.32b