Chapter 42

Circulation and Gas Exchange

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Overview: Trading Places

- Every organism must exchange materials with its environment.
- Exchanges ultimately occur at the cellular level.
- 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.
- *Internal transport and gas exchange are functionally related in most animals*.

How does a feathery fringe help this animal survive?

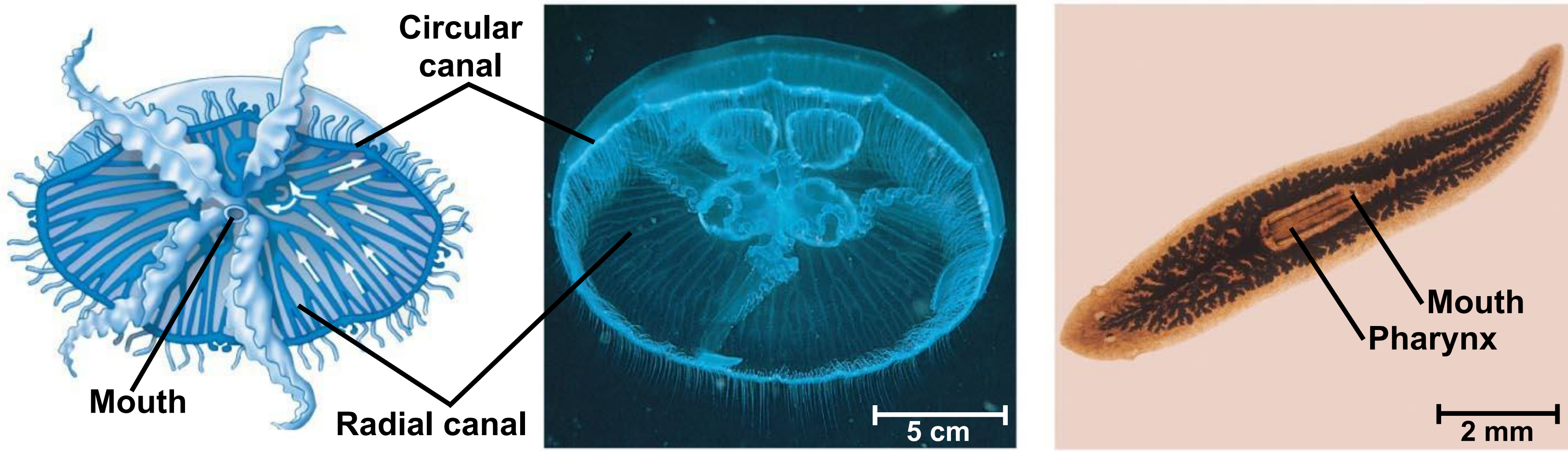
Circulatory systems link exchange surfaces with cells throughout the body

- In small and/or thin animals, cells can exchange materials directly with the surrounding medium.
- In most animals, ***transport systems connect the organs of exchange with the body cells***.
- Most complex animals have internal transport systems that circulate fluid.

Gastrovascular Cavities

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

Internal transport in gastrovascular cavities



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

(b) The planarian *Dugesia*, a flatworm

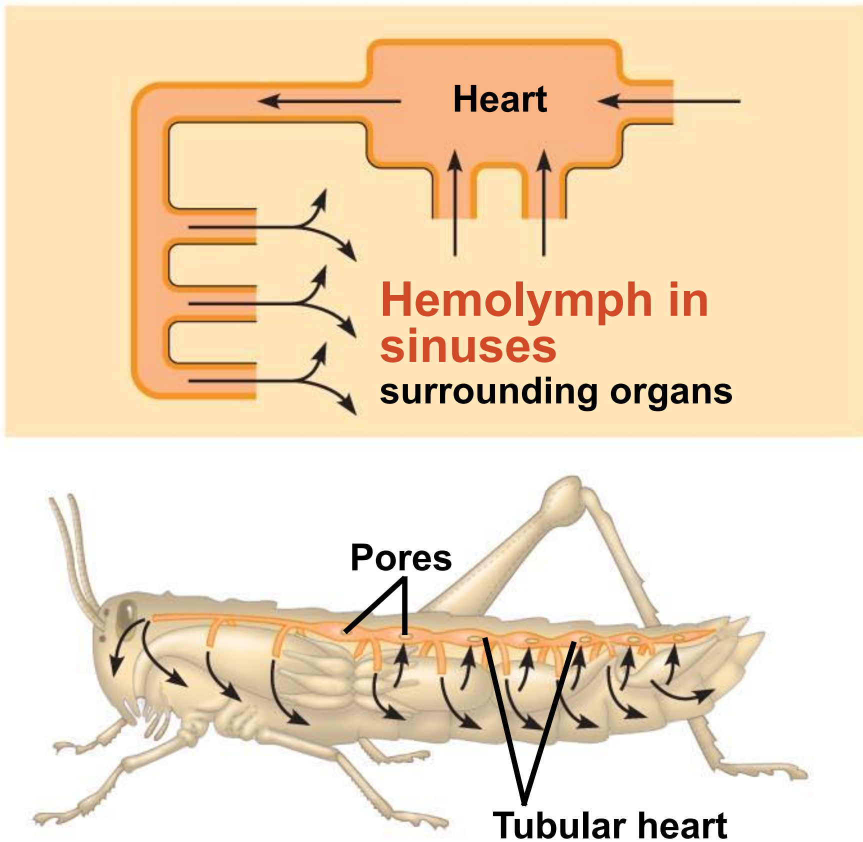
Open and Closed Circulatory Systems

- More complex animals have either open or closed **circulatory systems**.
- Both systems have three basic components:
  - A **circulatory fluid** = blood or hemolymph.
  - A set of tubes = **blood vessels**.
  - A muscular **pump** = the **heart**.

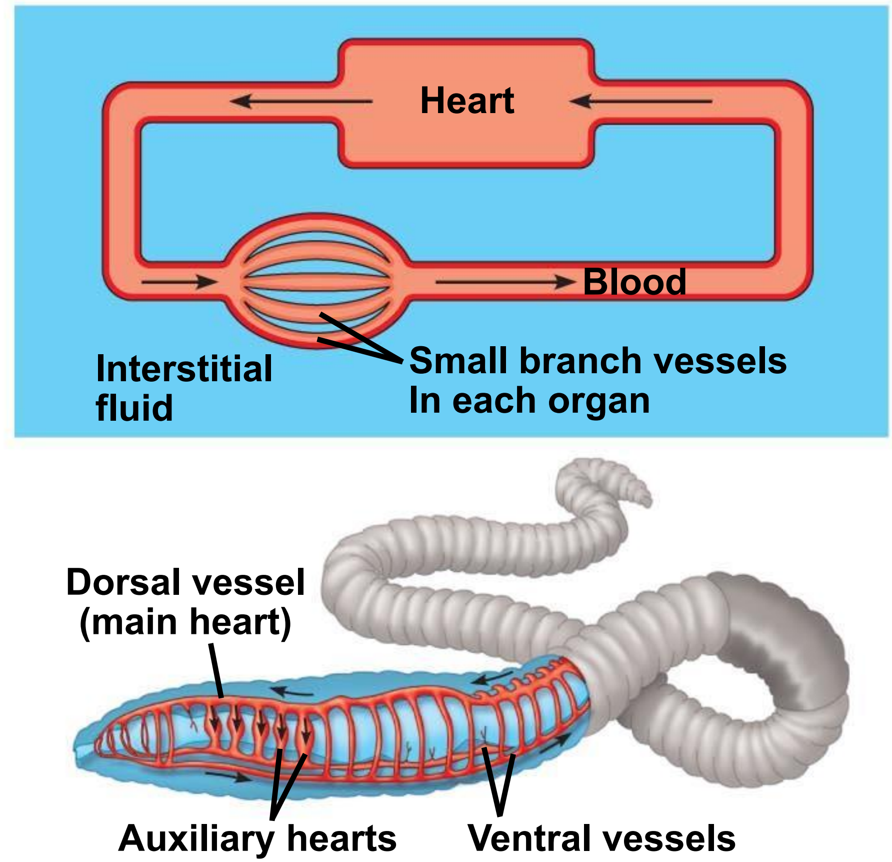
- In insects, other arthropods, and most molluscs, blood bathes the organs directly in an **open circulatory system**.
- In an open circulatory system, there is **no** distinction between blood and interstitial fluid, and this general body fluid is more correctly called **hemolymph**.

- In a **closed circulatory system**, the 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.

Open and closed circulatory systems



(a) An open circulatory system



(b) A closed circulatory system

Organization of Vertebrate Closed Circulatory Systems

- Humans and other vertebrates have a closed circulatory system, often called the **cardiovascular system**.
- The three main types of blood vessels are:

  arteries - away from the heart.

  veins - toward the heart.

  capillaries - exchange with body cells.

- **Arteries** branch into **arterioles** and carry blood 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.

- Vertebrate hearts contain two or more chambers.
- Blood enters through an **atrium** and is pumped out through a **ventricle.**

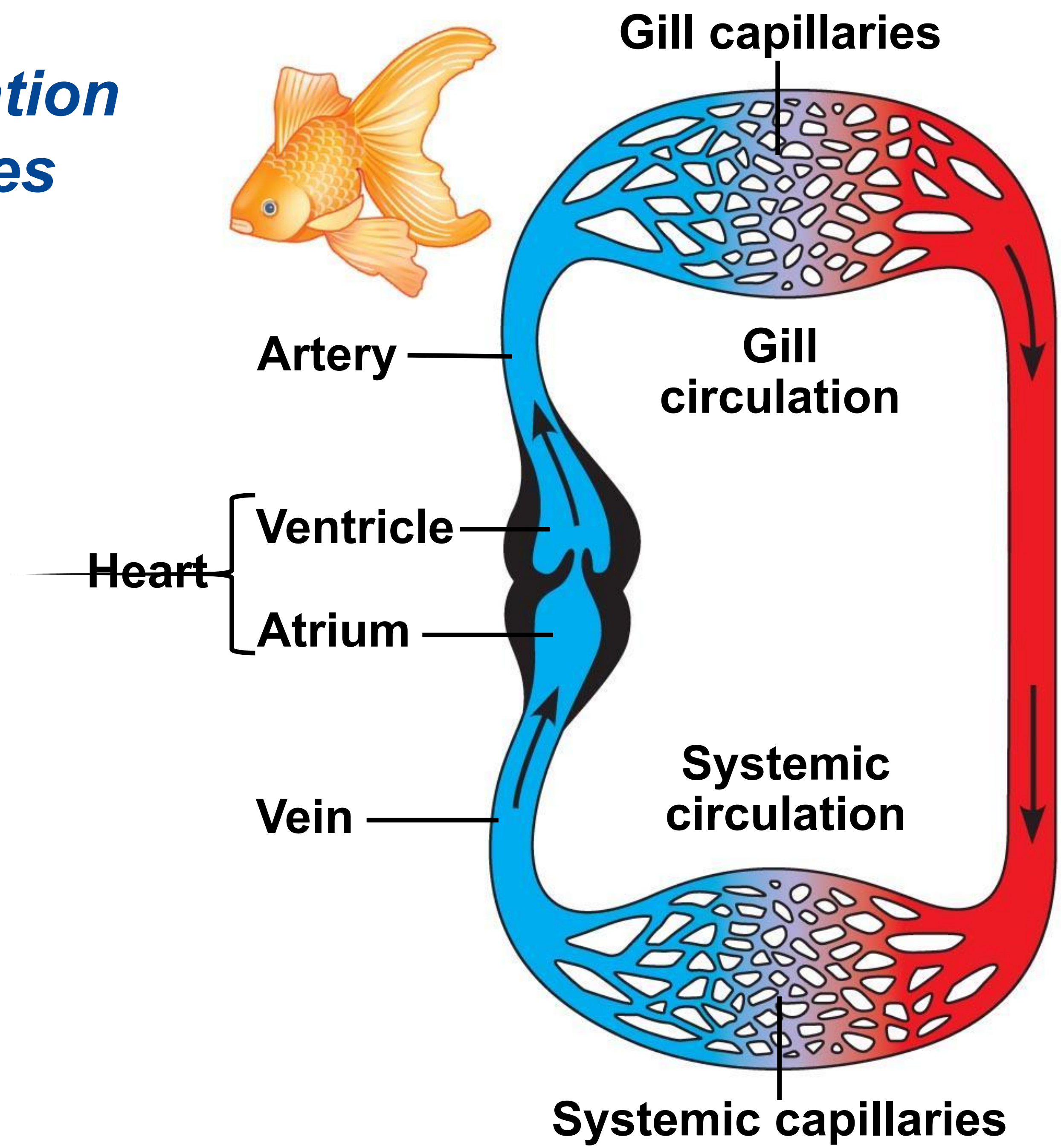
Atria - **receive** blood

Ventricles - **pump** blood

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.

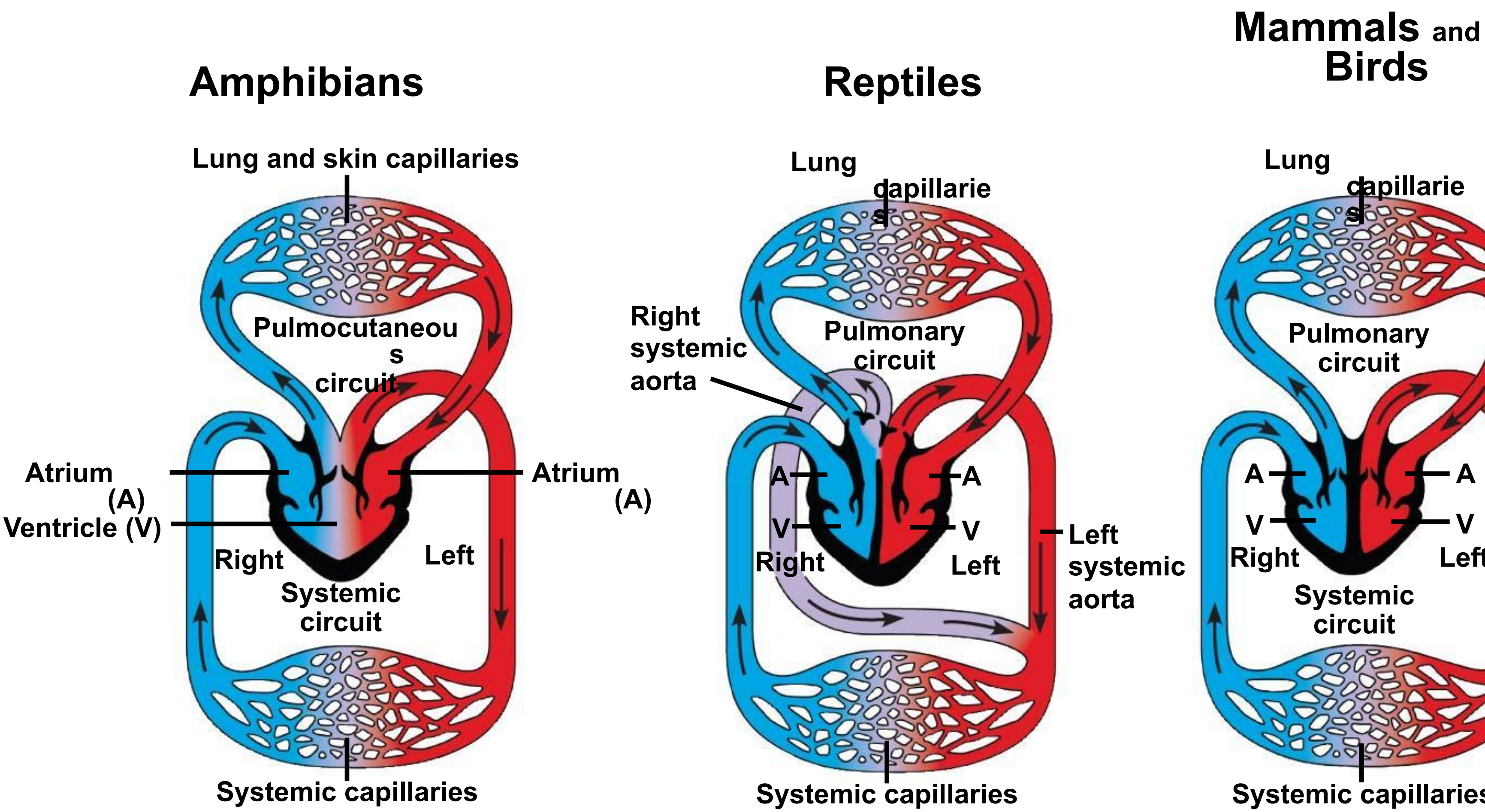
Single circulation in fishes



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.

Double circulation in vertebrates



- 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

Amphibians:

- Frogs / amphibians have a three-chambered heart: 2 atria and 1 ventricle.
- The ventricle pumps blood into a forked artery that splits the ventricle's output into the pulmocutaneous circuit and the systemic circuit.
- Underwater, blood flow to the lungs is nearly shut off.

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 - partially or fully divides the ventricle.
- Reptiles have double circulation, with a pulmonary circuit - lungs and a systemic circuit.

RA --> RV --> LUNGS --> LA --> LV --> Body

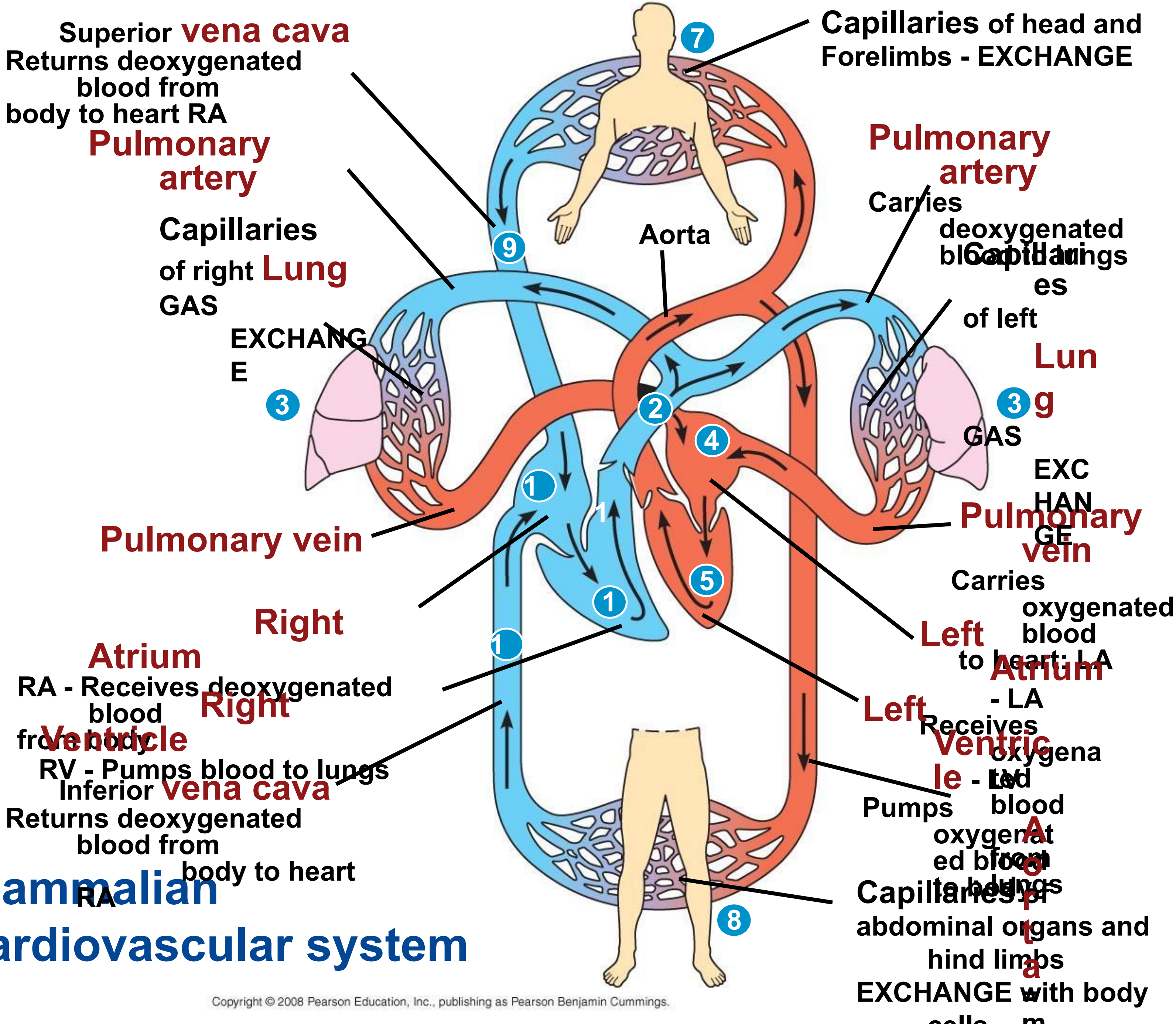
Mammals

- 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*.

Coordinated cycles of heart contraction drive double circulation in mammals

- 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** (deoxygenated blood from head, neck, and forelimbs) and inferior vena cava (deoxygenated blood from trunk and hind limbs).
- The superior vena cava and inferior vena cava flow **into** the Right Atrium - **RA**.

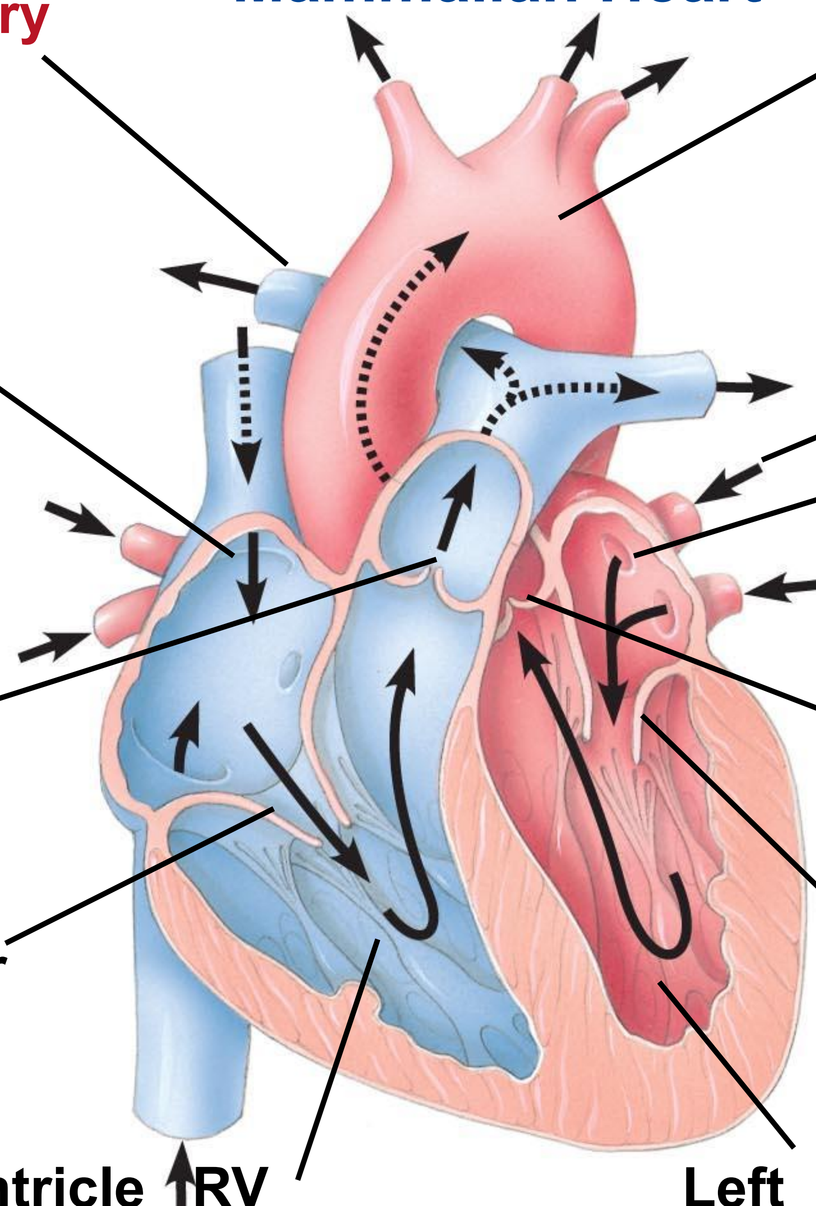


mammalian cardiovascular system

The Mammalian Heart: *A Closer Look*

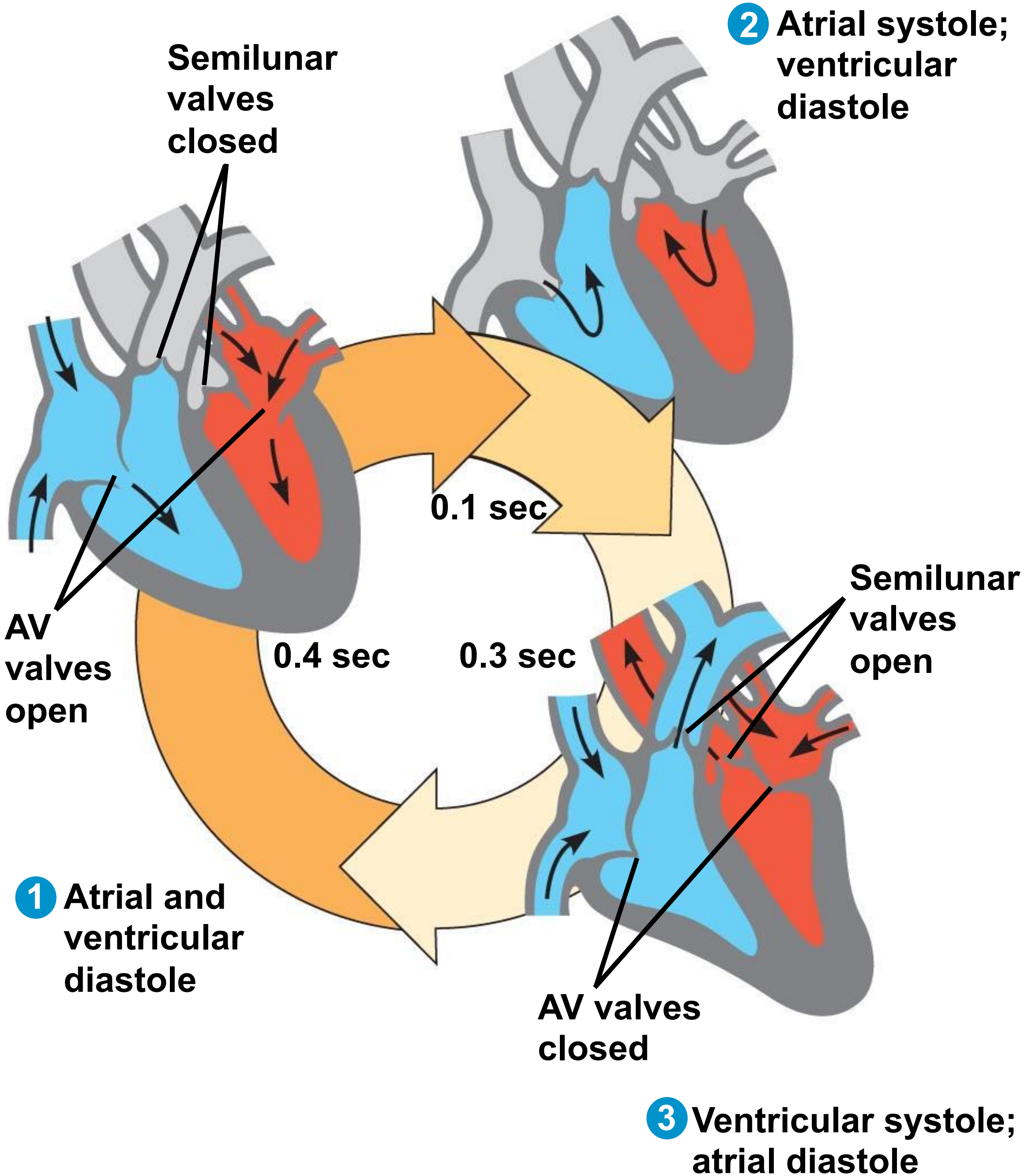
- A closer look at the mammalian **heart** provides a better understanding of double circulation.
- RIGHT side = deoxygenated blood from body pumped to lungs.
- LUNGS = gas exchange.
- LEFT side = oxygenated blood from lungs pumped to body.

Mammalian Heart



- 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.**
- **Blood Pressure = systolic / diastolic**

Cardiac cycle



- 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.

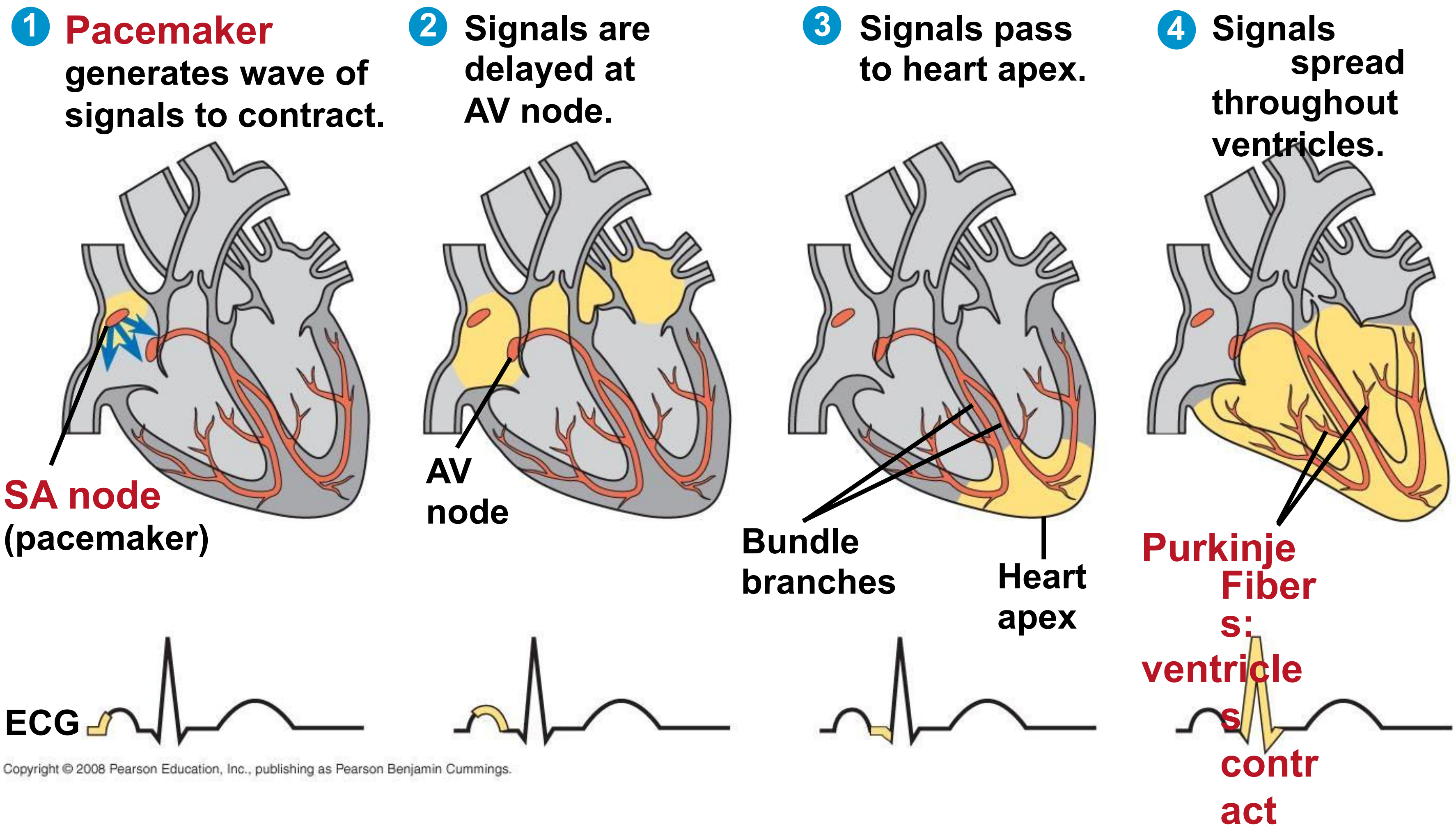
Four **valves prevent backflow** of blood in the heart:

- 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 = 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 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.
- Impulses that travel during the cardiac cycle can be recorded as an **electrocardiogram** (**ECG** or **EKG**). The pacemaker is influenced by nerves, hormones, body temperature, and exercise.

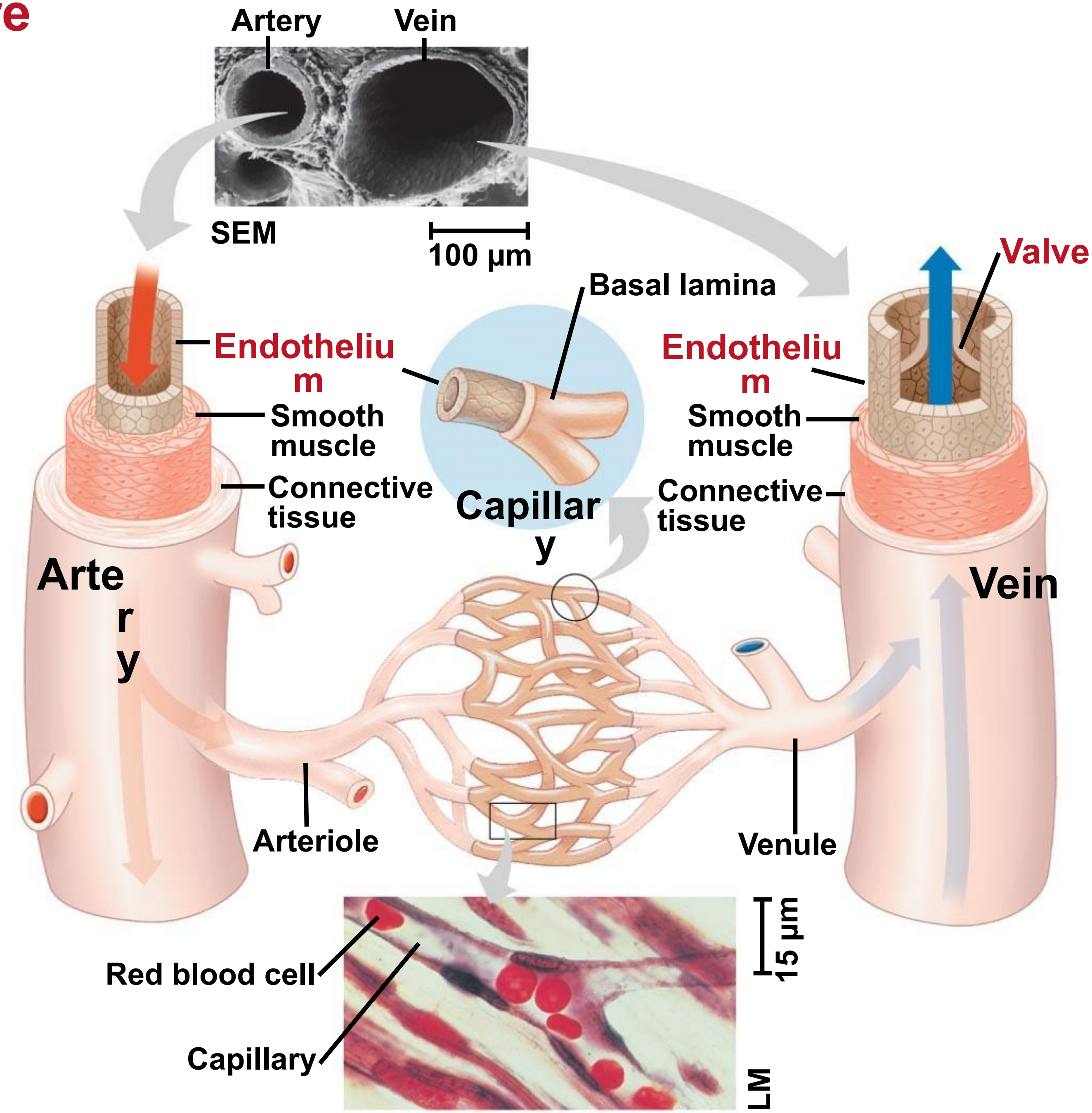
Control of heart rhythm



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.
- The epithelial layer that lines blood vessels is called the **endothelium**.

Structure of blood vessels

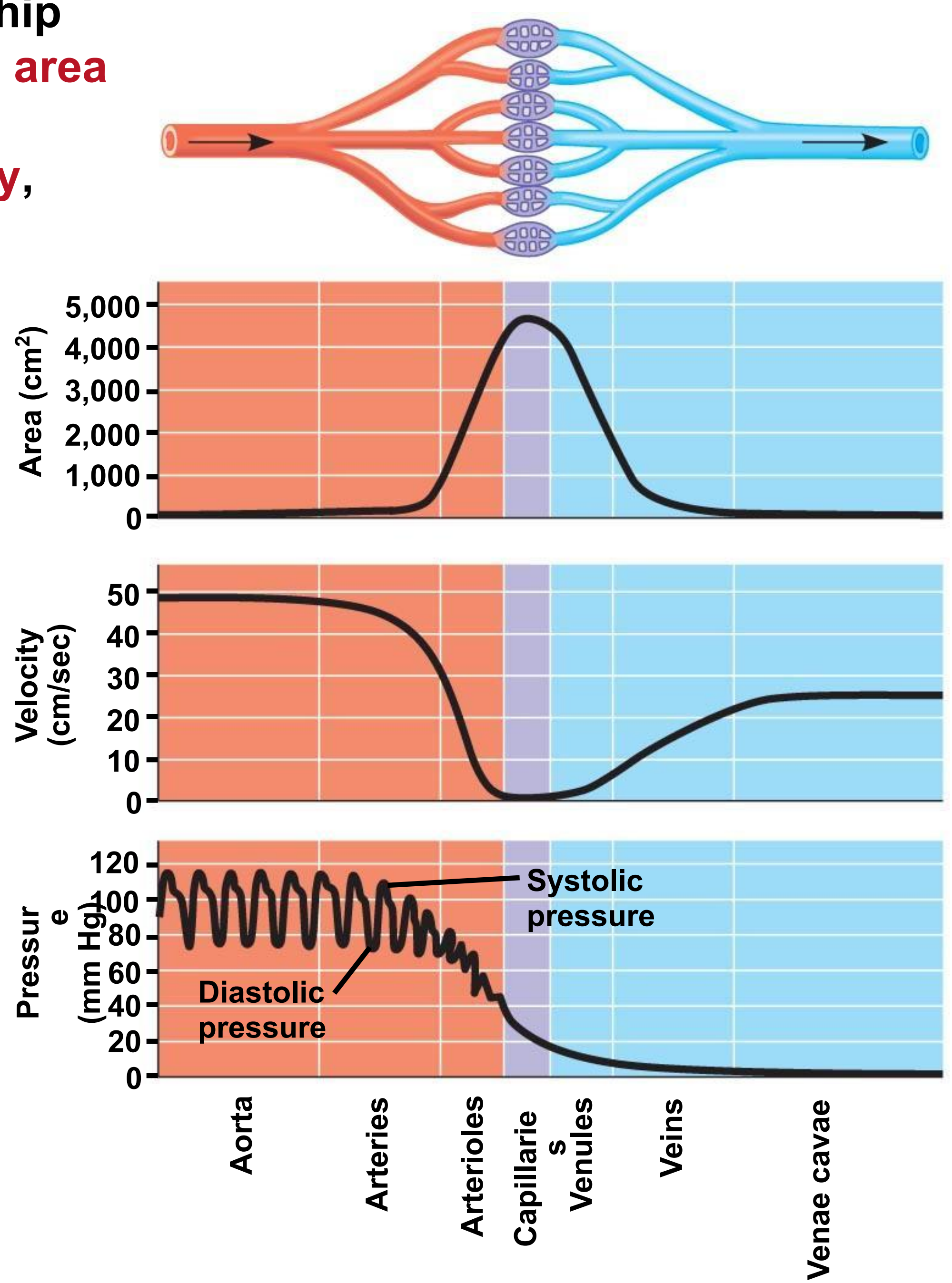


- Capillaries have thin walls, the endothelium plus its basement membrane, to facilitate the exchange of materials.
- Arteries and veins have an endothelium, smooth muscle, and connective tissue.
- Arteries have thicker walls than veins to accommodate the high pressure of blood pumped from the heart.
- 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*.

The interrelationship of cross-sectional area of blood vessels, blood flow velocity, and blood pressure.



Blood Pressure

- Blood pressure is the hydrostatic 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 ventricle contraction /systole; it is the highest pressure in the arteries.
- **Diastolic pressure** is the pressure in the arteries during relaxation /diastole; it is lower than systolic pressure.
- A **pulse** is the rhythmic bulging of artery walls with each heartbeat.

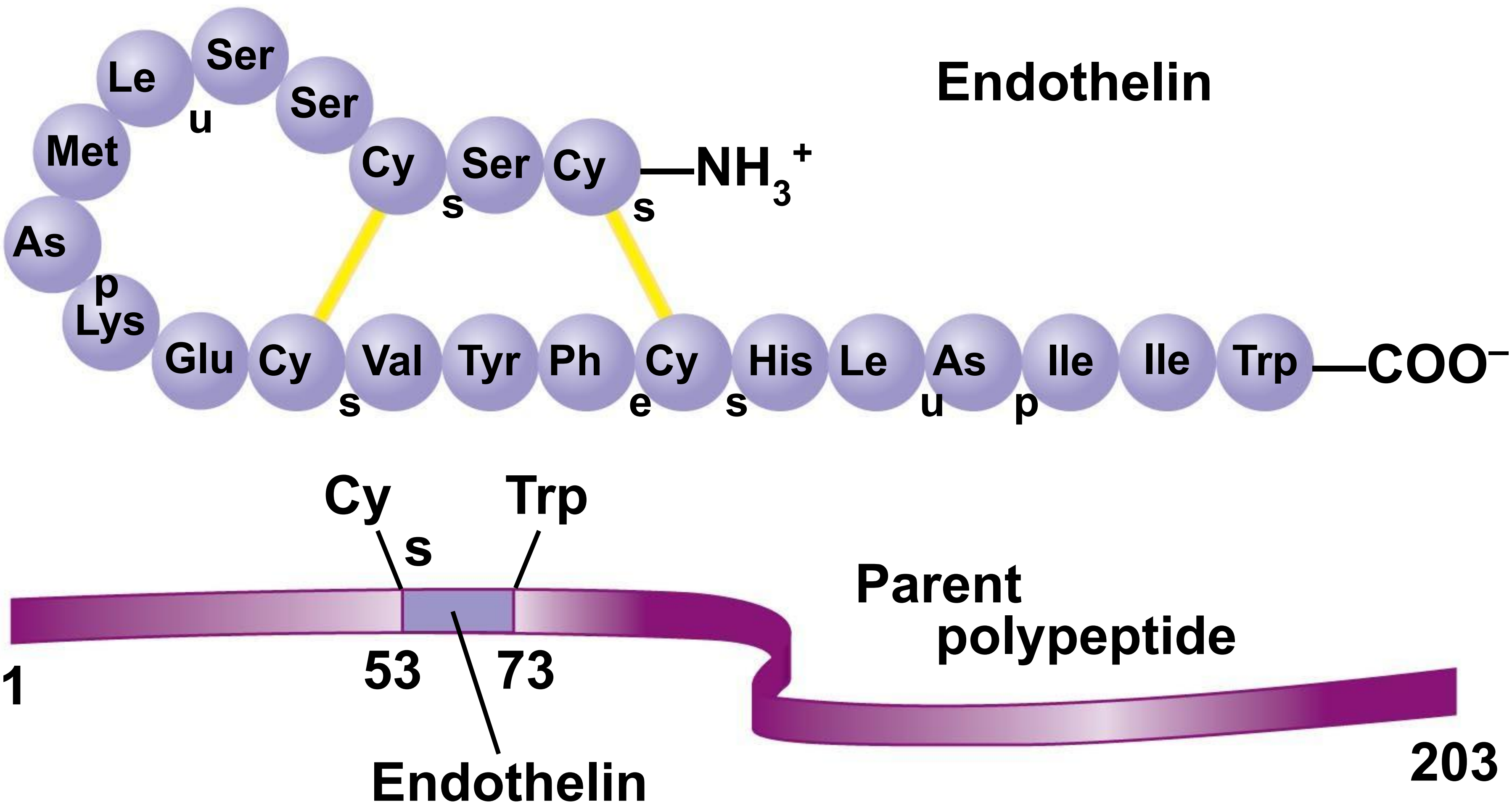
Regulation of Blood Pressure

- 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.

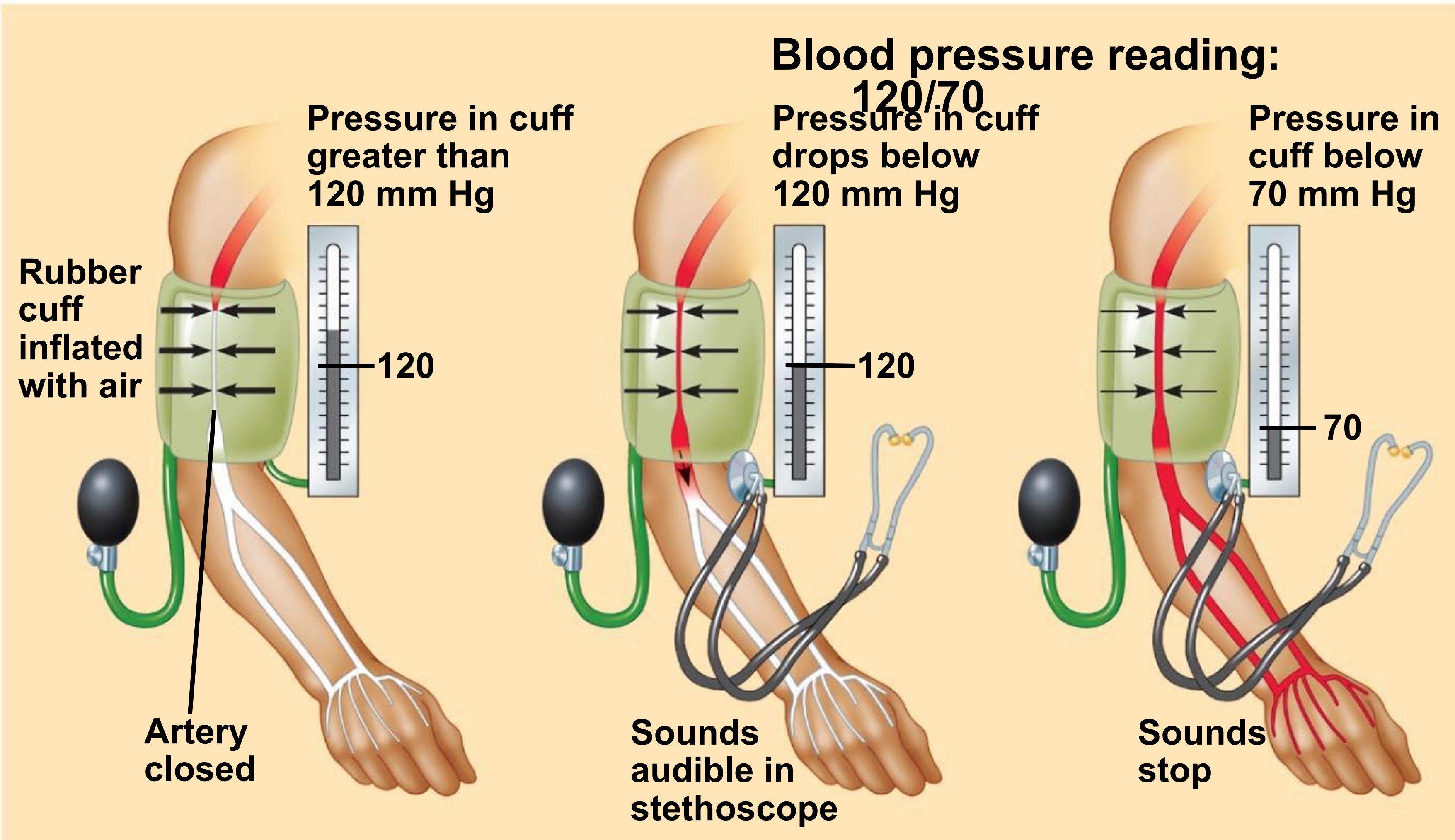
- ***Vasoconstriction*** and ***vasodilation*** help maintain adequate *blood flow* as the body's demands change.
- The peptide **endothelin** is an important inducer of vasoconstriction.
- Blood pressure is generally measured for an artery in the arm at the same height as the heart.
- Blood pressure for a healthy 20 year old at rest is 120 mm Hg at systole / 70 mm Hg at diastole.

Question: How do endothelial cells control vasoconstriction?

RESULTS

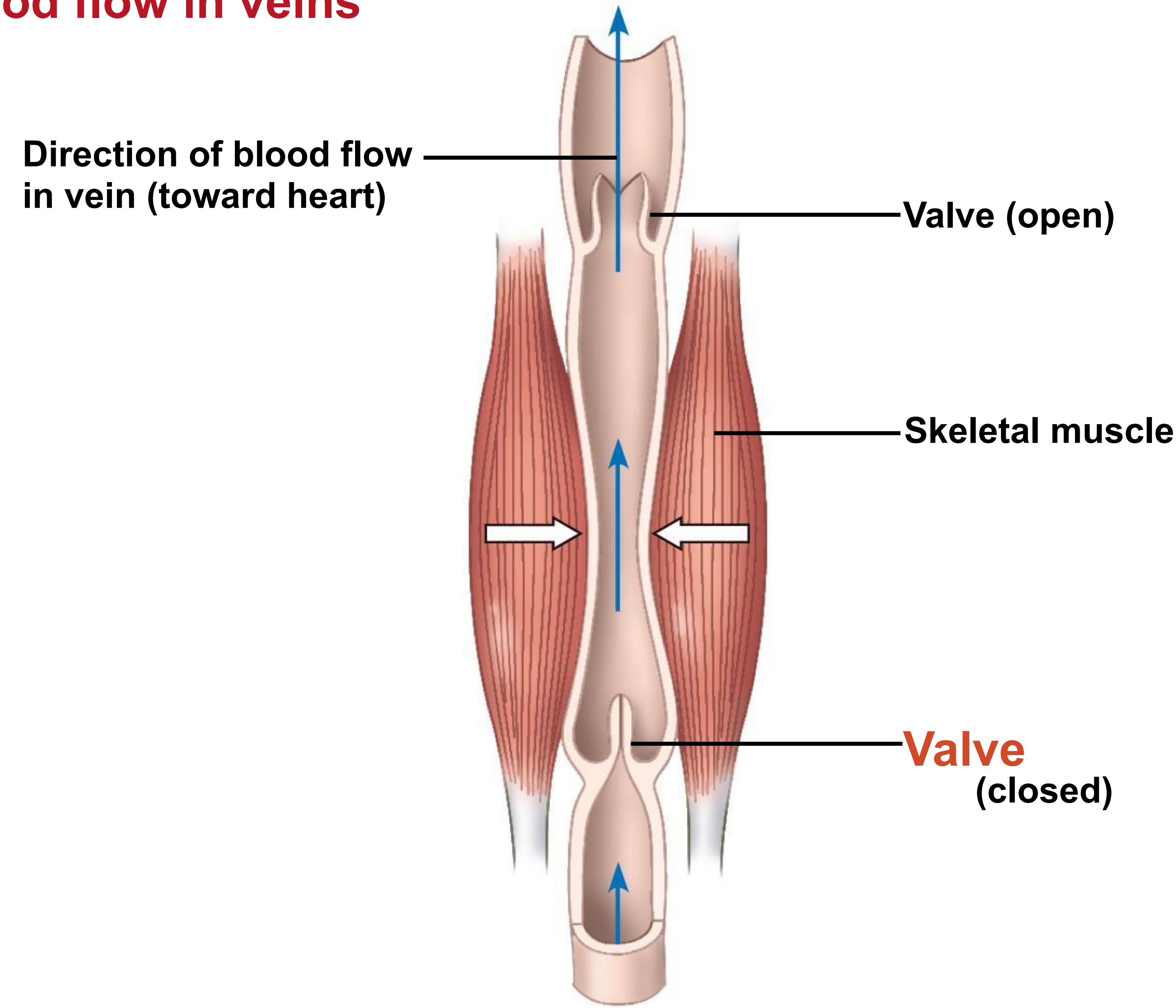


Measurement of blood pressure: sphygmomanometer



- 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 / heart prevent backflow of blood.***

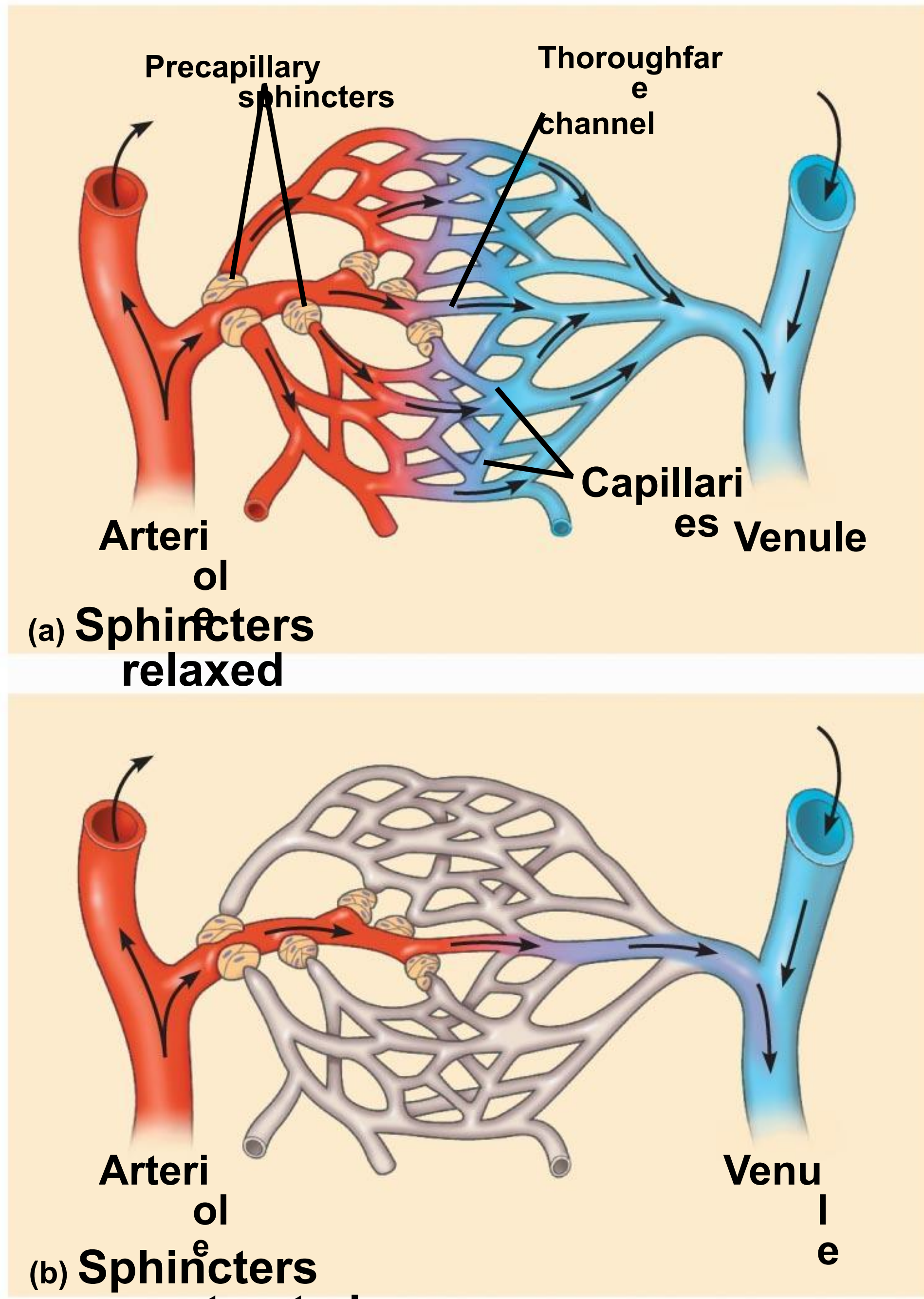
Blood flow in veins



Capillary Function

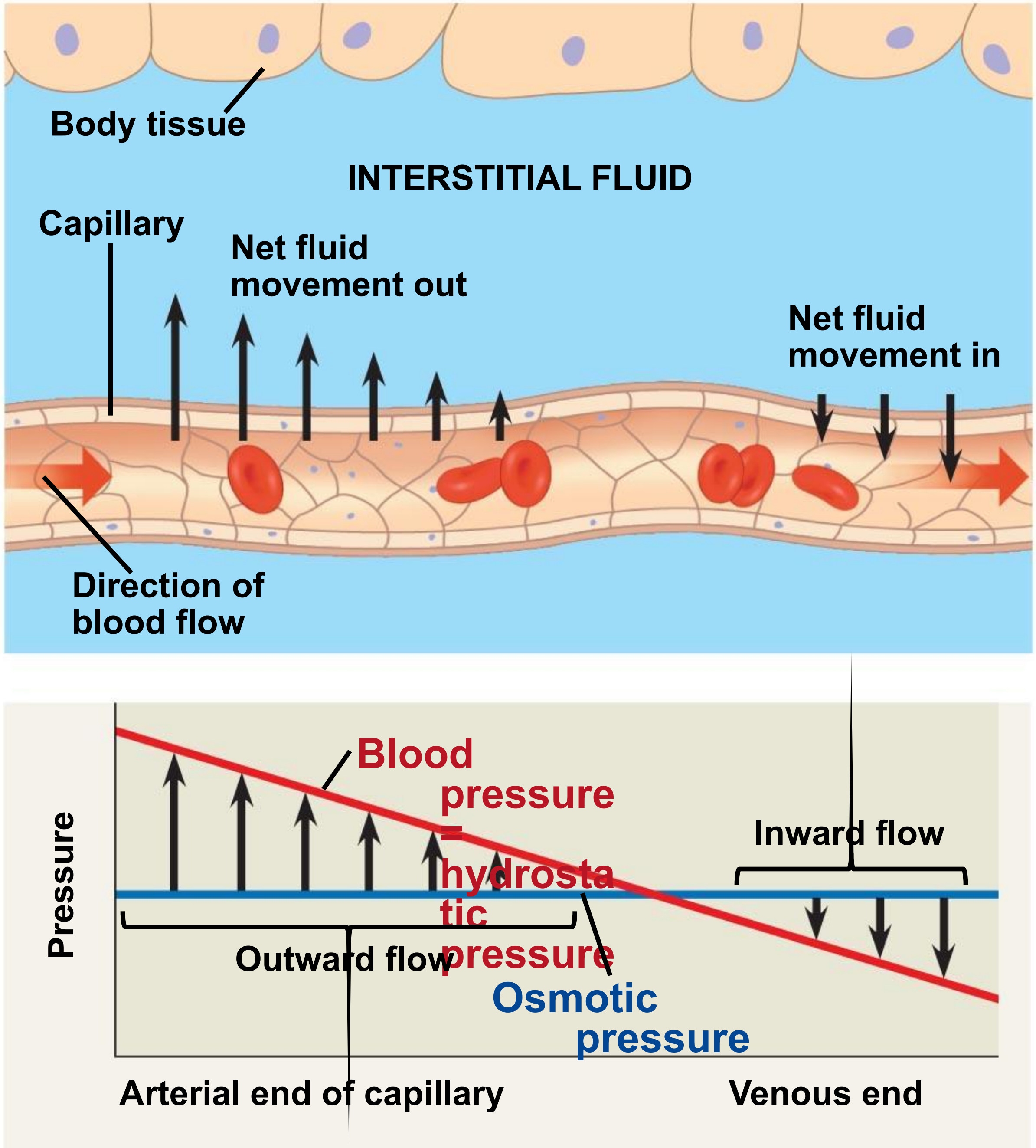
- Capillaries in major organs are usually filled to capacity. Blood supply varies in many other sites.
- Two mechanisms regulate distribution of blood in **capillary beds**:
  - *Contraction of the smooth muscle* layer in the wall of an *arteriole* constricts the vessel.
  - *Precapillary sphincters* control flow of blood between arterioles and venules.

Blood flow in capillary beds



- The critical ***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.

Fluid exchange between capillaries and the interstitial fluid



Fluid Return by the Lymphatic System

- The **lymphatic system** - returns fluid that leaks out in the capillary beds … restoring filtered fluid to blood maintains homeostasis.
- This system aids in body defense.
- 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 neck veins.

- **Lymph nodes** are organs that produce phagocytic white blood cells and filter lymph - an important role in the body’s defense.
- Edema is swelling caused by disruptions in the flow of lymph.

Blood Composition and Function

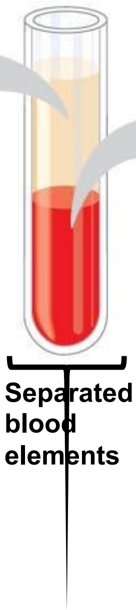
- Blood consists of several kinds of **blood cells** suspended in a liquid matrix called **plasma**.
- The cellular elements: red blood cells, white blood cells, and platelets occupy about 45% of the volume of blood.

Composition of mammalian blood

Plasma 55%

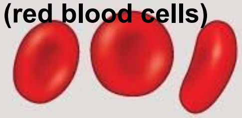
Constituent	Major functions
Water	Solvent for carrying other substances
Ions (blood electrolytes) Sodium Potassium Calcium Magnesium Chloride Bicarbonate	Osmotic balance, pH buffering, and regulation of membrane permeability
Plasma proteins Albumin	Osmotic balance pH buffering
Fibrinogen	Clotting
Immunoglobulins (antibodies)	Defense

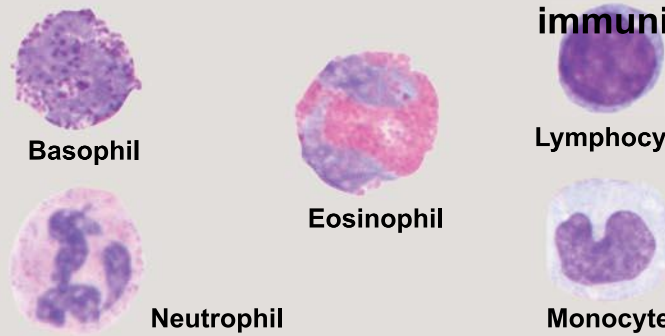
Substances transported by blood
- Nutrients (such as glucose, fatty acids, vitamins)
- Waste products of metabolism
- Respiratory gases (O_2 and CO_2)
- Hormones



Cellular elements 45%

Cell type	Number per µL (mm^3) of blood	Functions
Erythrocytes (red blood cells)	5–6 million	Transport oxygen and help transport carbon dioxide
Leukocytes (white blood cells) Basophil Eosinophil Lymphocyte Neutrophil Monocyte	5,000–10,000	Defense and immunity
Platelets	250,000–400,000	Blood clotting





Plasma

- Blood plasma is about 90% water.
- Among its solutes are inorganic salts in the form of dissolved ions, sometimes called electrolytes.
- Another important class of solutes is the plasma proteins, which influence blood pH, osmotic pressure, and viscosity. Various plasma proteins function in lipid transport, immunity, and blood clotting.
- Plasma transports nutrients, gases, and cell waste.

Cellular Elements

- Suspended in blood plasma are two types of cells:
  - Red blood cells rbc = ***erythrocytes***, transport *oxygen*.
  - White blood cells wbc = ***leukocytes***, function in *defense*.
- ***Platelets*** are fragments of cells that are involved in *blood clotting*.

Erythrocytes - Oxygen Transport

- Red blood cells, or **erythrocytes**, are by far the *most numerous blood cells*.
- They transport oxygen throughout the body.
- They contain **hemoglobin**, the iron-containing protein that transports oxygen.

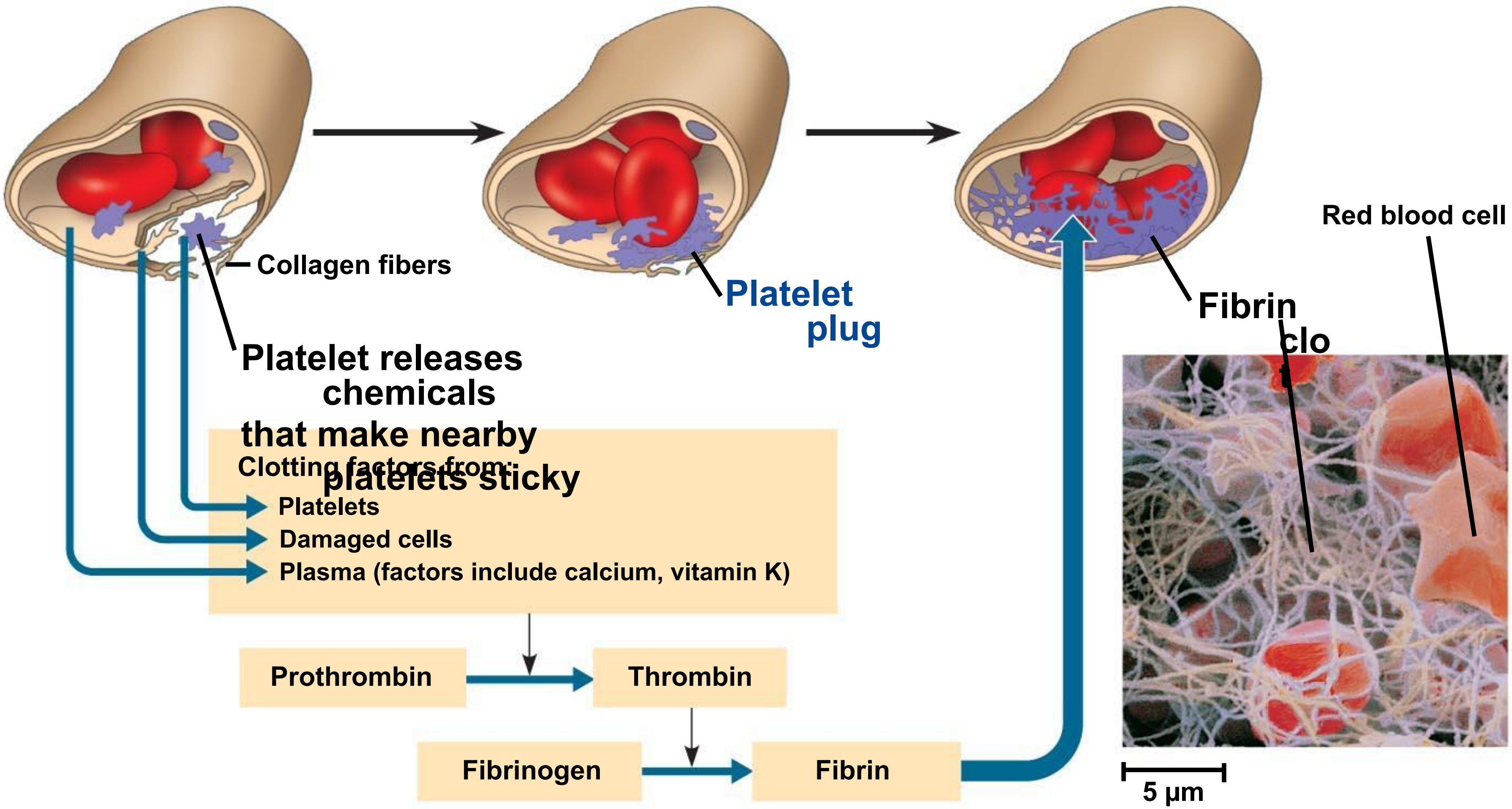
Leukocytes - Defense

- There are five major types of white blood cells, or **leukocytes**: monocytes, neutrophils, basophils, eosinophils, and lymphocytes.
- They function in defense by phagocytizing bacteria and debris or by producing antibodies.
- They are found both in and outside of the circulatory system.

Platelets - Blood Clotting

- Platelets are fragments of cells and function in blood clotting.
- When the endothelium of a blood vessel is damaged, the clotting mechanism begins.
- A cascade of complex reactions converts fibrinogen to **fibrin**, forming a clot.
- *A blood clot formed within a blood vessel is called a **thrombus** and can block blood flow.*

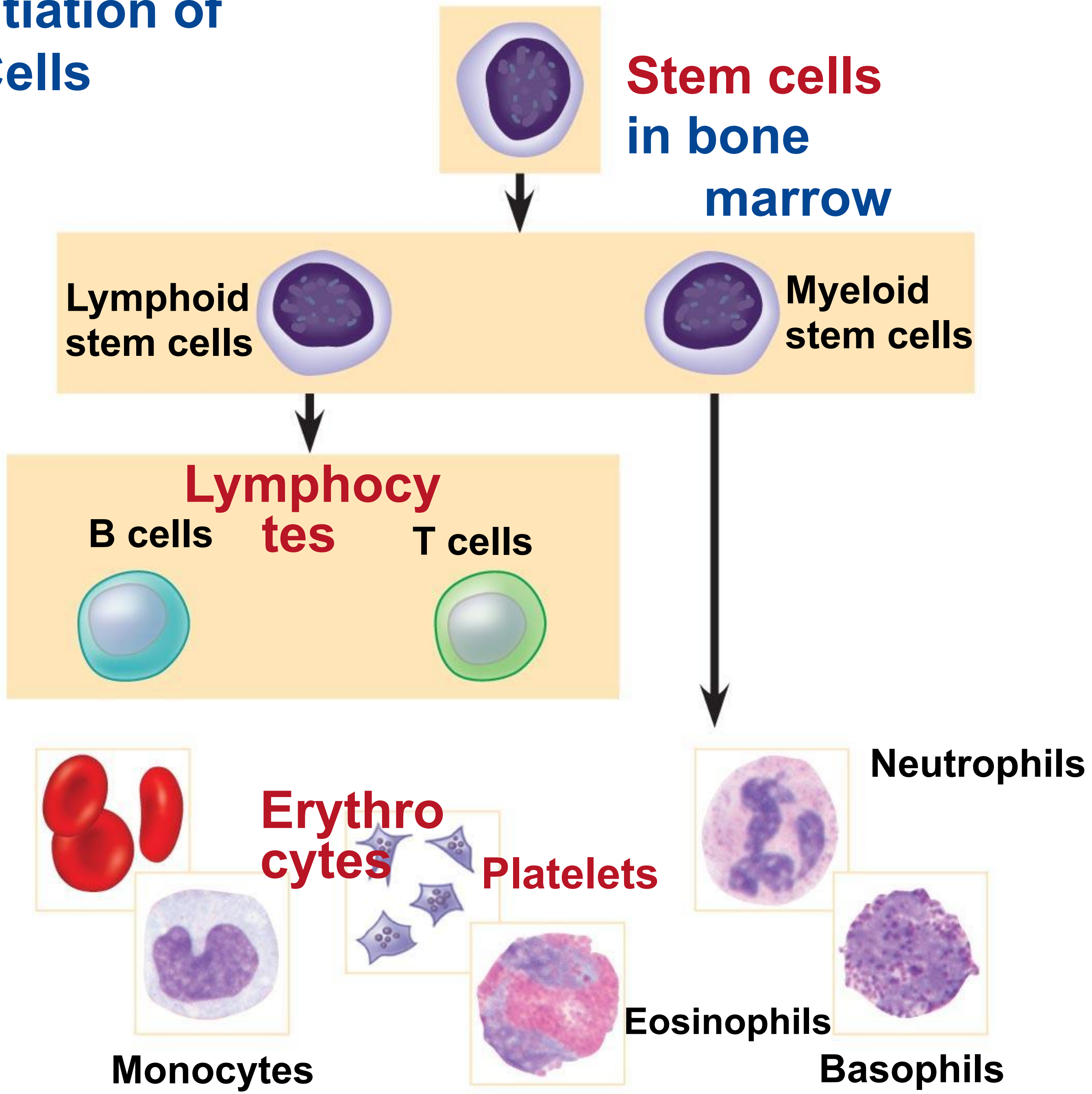
Blood clotting



Stem Cells and the Replacement of Cellular Elements

- The cellular elements of blood wear out and are replaced constantly throughout a person's life.
- Erythrocytes, leukocytes, and platelets all develop from a common source of **stem cells** in the red marrow of bones.
- The hormone **erythropoietin** (EPO) stimulates erythrocyte production when oxygen delivery is low.

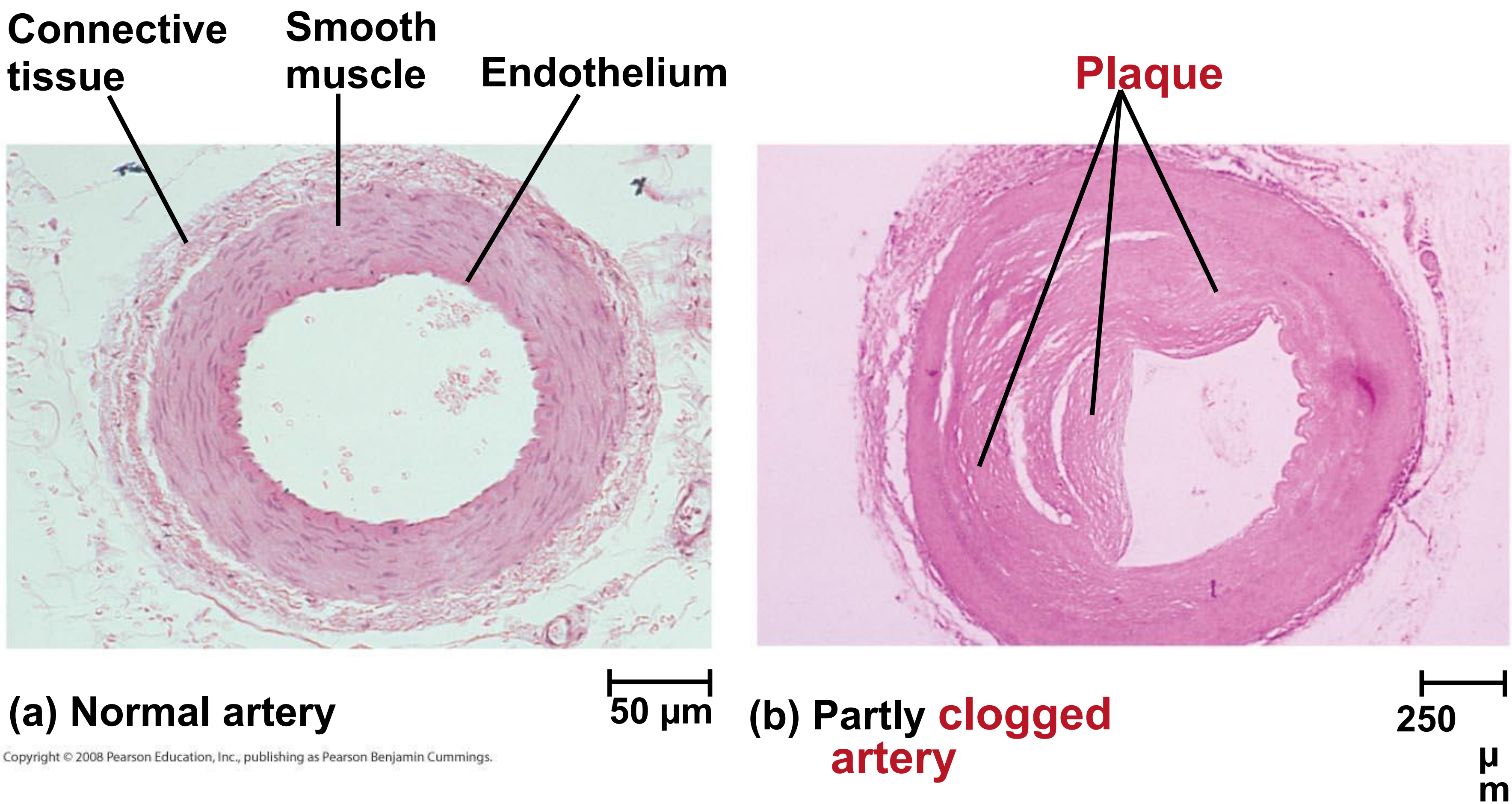
Differentiation of Blood Cells



Cardiovascular Disease = Disorders of the Heart and the Blood Vessels

- One type of cardiovascular disease, **atherosclerosis**, is caused by the buildup of plaque deposits within arteries.
- A **heart attack** is the **death of cardiac muscle** tissue resulting from **blockage** of one or more coronary arteries.
- A **stroke** is the **death of nervous tissue** in the brain, usually resulting from **rupture** or **blockage** of arteries in the brain /head.

Atherosclerosis



(a) Normal artery

(b) Partly clogged artery

Treatment and Diagnosis of Cardiovascular Disease

- **Cholesterol** is a major contributor to atherosclerosis.
- **Low-density lipoproteins (LDLs)** = "bad cholesterol," are associated with plaque formation.
- **High-density lipoproteins (HDLs)** = "good cholesterol," reduce the deposition of cholesterol.
- **Hypertension =** high blood pressure, promotes atherosclerosis and increases the risk of heart attack and stroke.
- Hypertension can be reduced by dietary changes, exercise, and/or medication.

Gas exchange occurs across specialized respiratory surfaces

- **Gas exchange** supplies oxygen for cellular respiration and disposes of carbon dioxide. Gases diffuse down pressure gradients in the lungs and other organs as a result of **differences** in **partial pressure**.
- ***Partial pressure*** *is the pressure exerted by a particular gas in a mixture of gases*. A gas diffuses from a region of higher partial pressure to a region of lower partial pressure: ***H --> L***
- In the lungs and tissues, O_2 *and* CO_2 *diffuse from where their partial pressures are higher* to *where they are lower*.

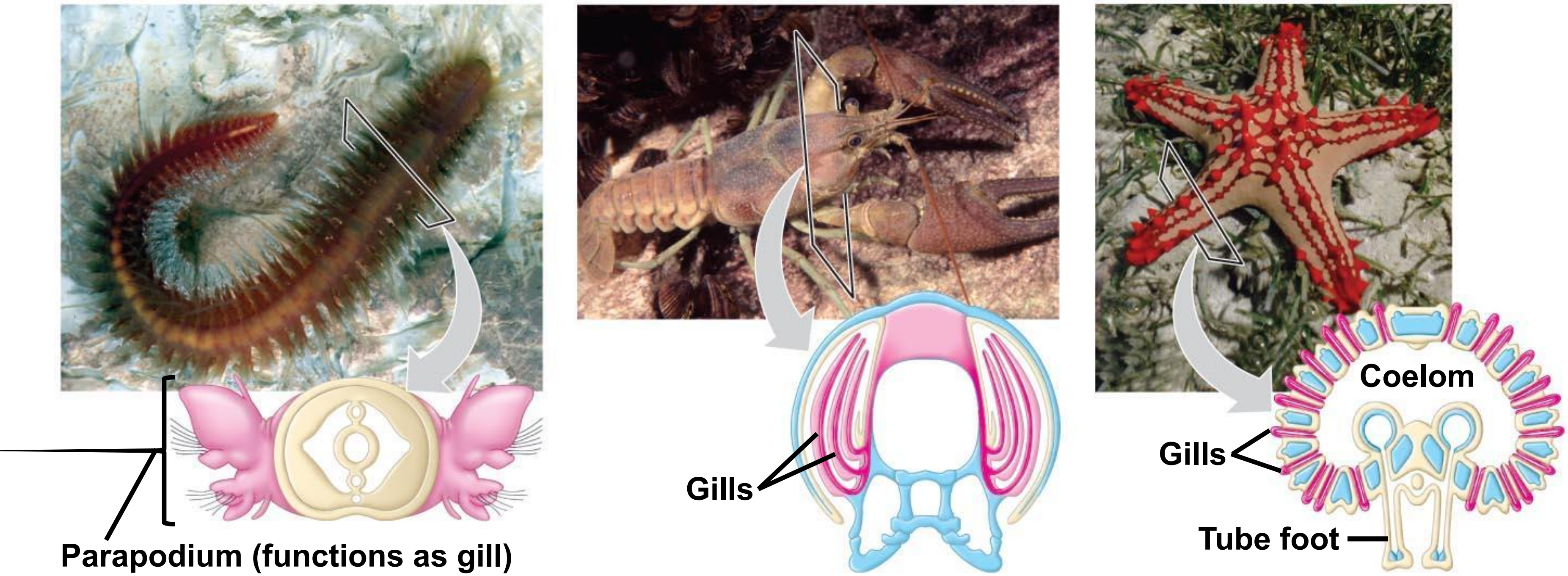
Respiratory Media

- 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.

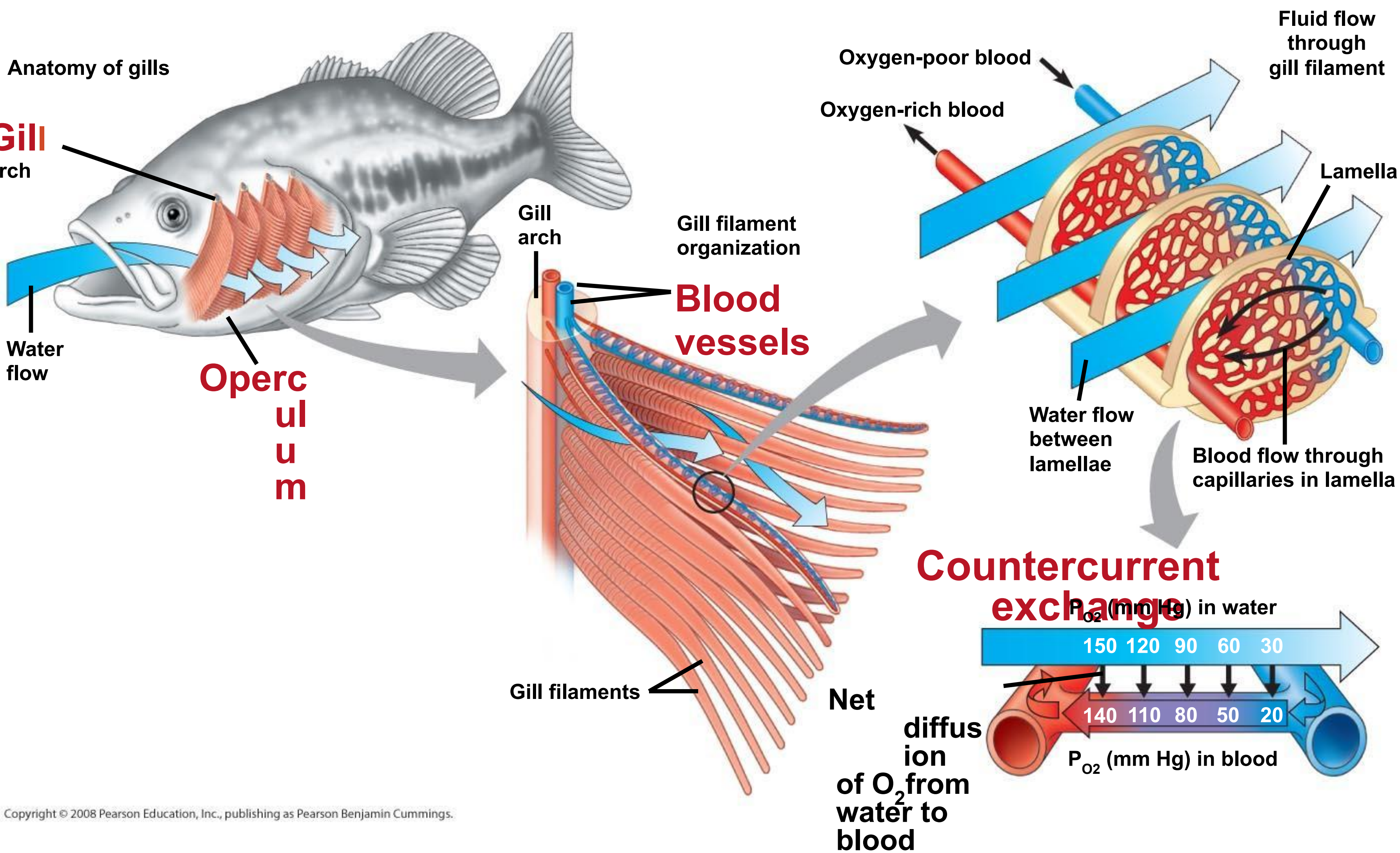
Gills are outfoldings of the body that create a large surface area for gas exchange



(a) Marine worm (b) Crayfish (c) Sea star

- **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… maximizes diffusion.

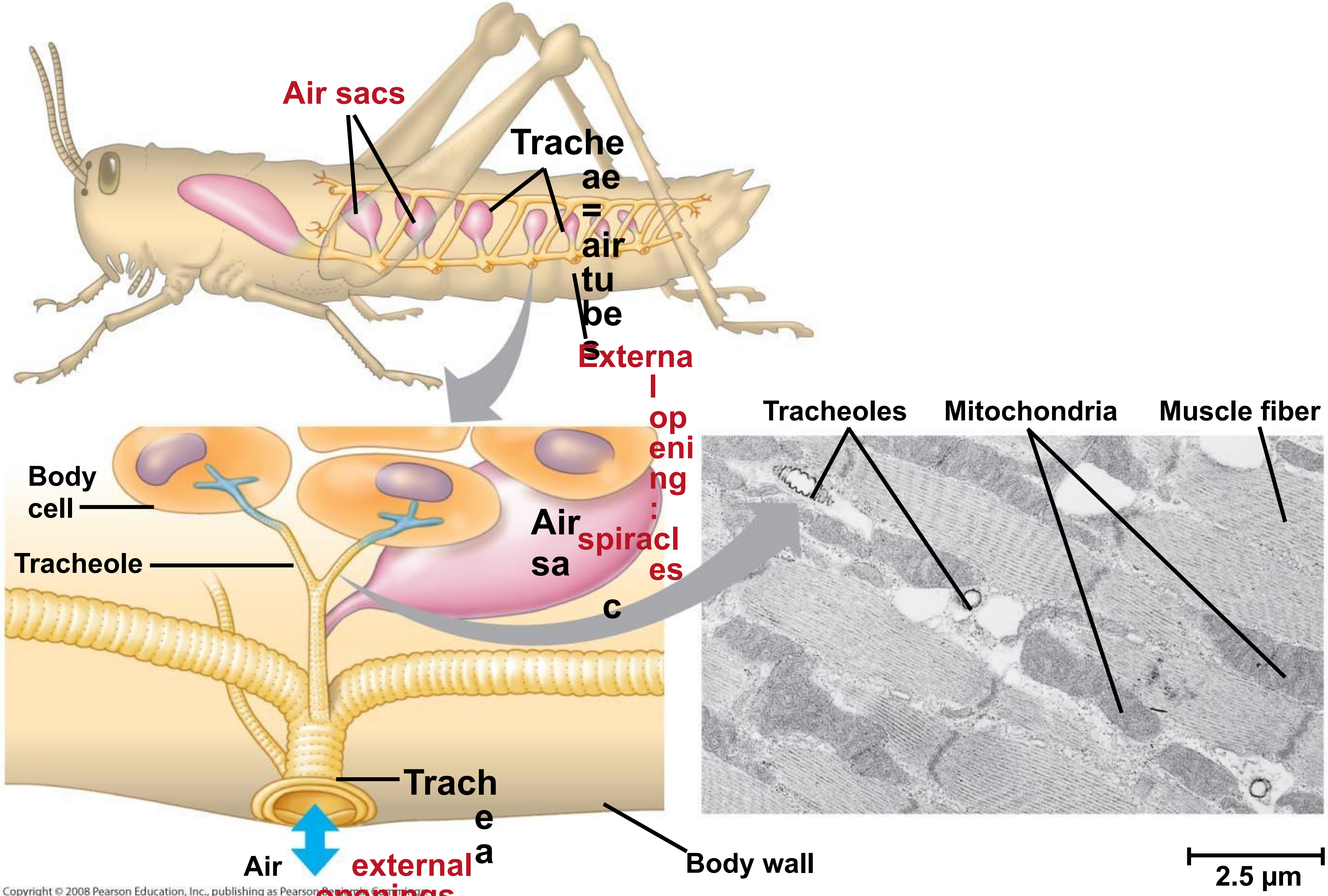
Structure and function of fish gills



Tracheal Systems in Insects

- The **tracheal system** of insects consists of tiny branching tubes that penetrate the body.
- The *tracheal tubes supply O_2 directly to body cells*.
- *The **respiratory** and **circulatory systems** are **separate.***
- Larger insects must ventilate their tracheal system to meet O_2 demands.

Tracheal systems



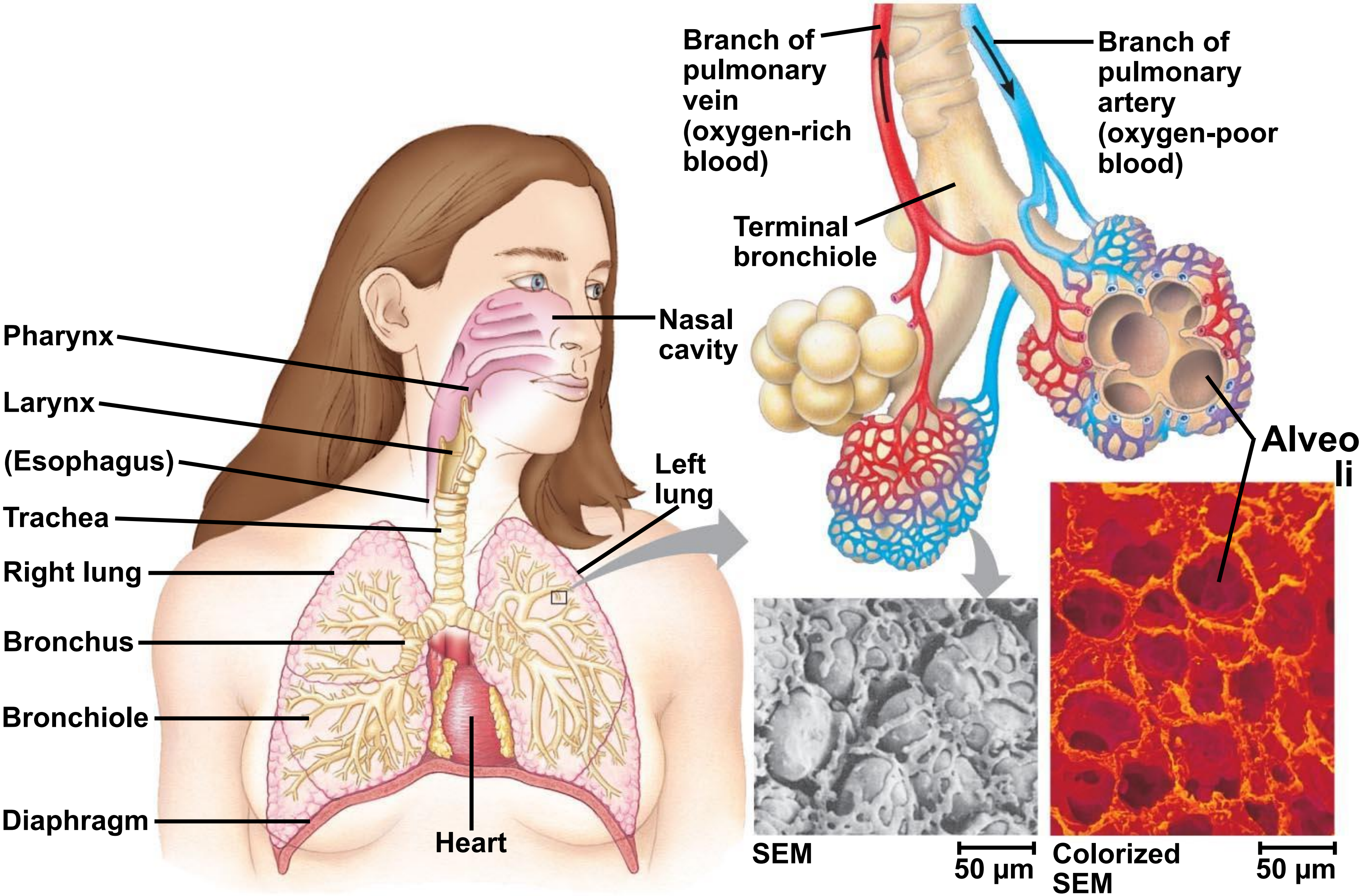
Lungs = Infoldings of the body surface

- 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 / air tubes conveys air to the lungs.
- Air inhaled through the ***nostrils*** --> ***pharynx*** --> **larynx** --> ***trachea*** --> ***bronchi*** --> ***bronchioles*** --> ***alveoli*** = *site of gas exchange*.
- Exhaled air passes over the **vocal cords** to create sounds.
- *Alveoli are wrapped by capillaries for GAS EXCHANGE*.

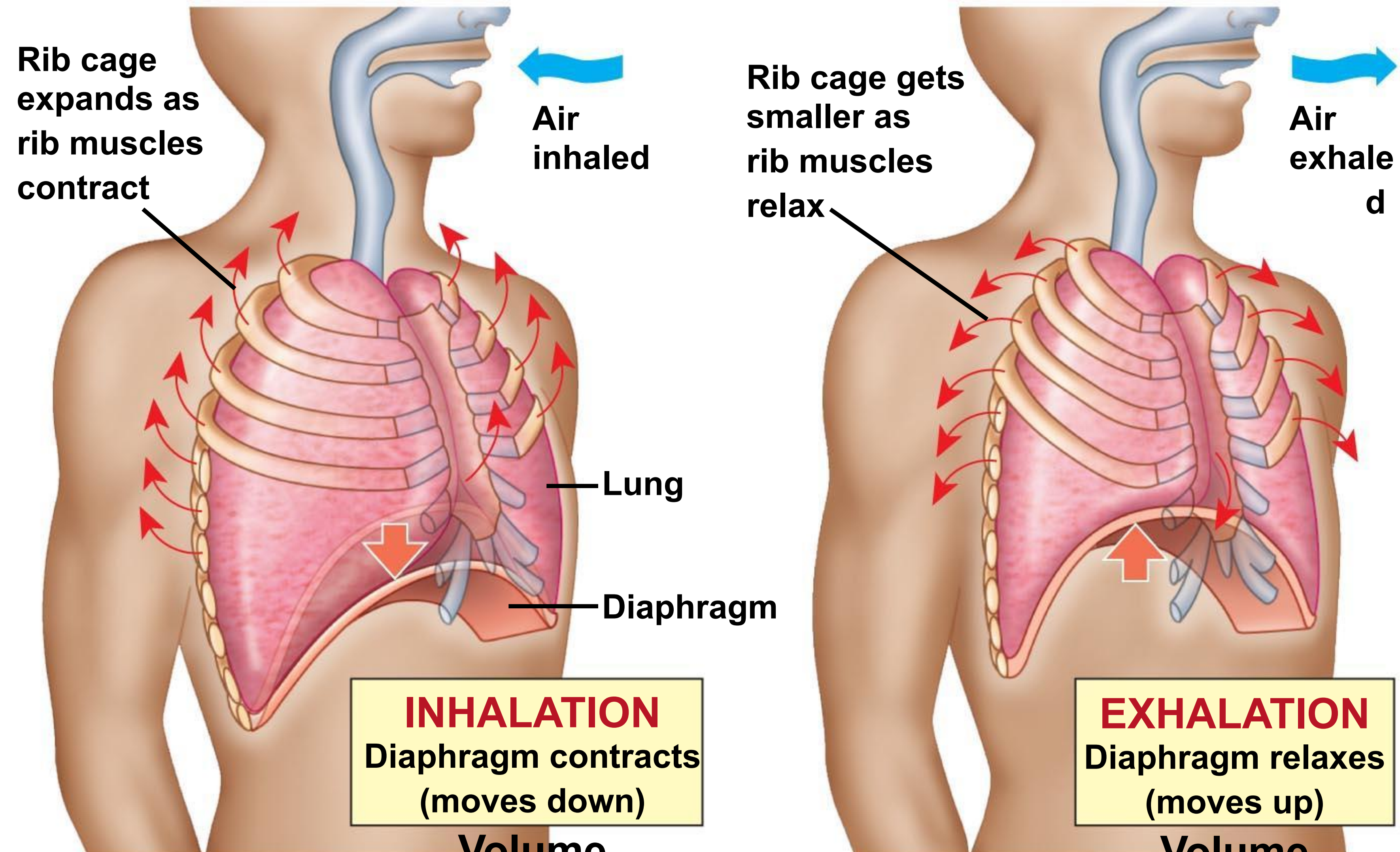
Mammalian Respiratory System



Breathing Ventilates the Lungs by Inhalation and Exhalation of Air

- Amphibians, such as a frog, ventilates its lungs by **positive pressure breathing**, which forces air down the trachea.
- Mammals ventilate by **negative pressure breathing**, which pulls air into the lungs by varying volume / air pressure. Lung volume increases as the rib muscles and **diaphragm** contract.
- The ***tidal volume*** is the *volume of air inhaled with each breath*. The *maximum* tidal volume is the ***vital capacity***. After exhalation, ***residual volume*** *of air remains in the lungs.*

Negative pressure breathing: H --> L



Volume increases

Pressure

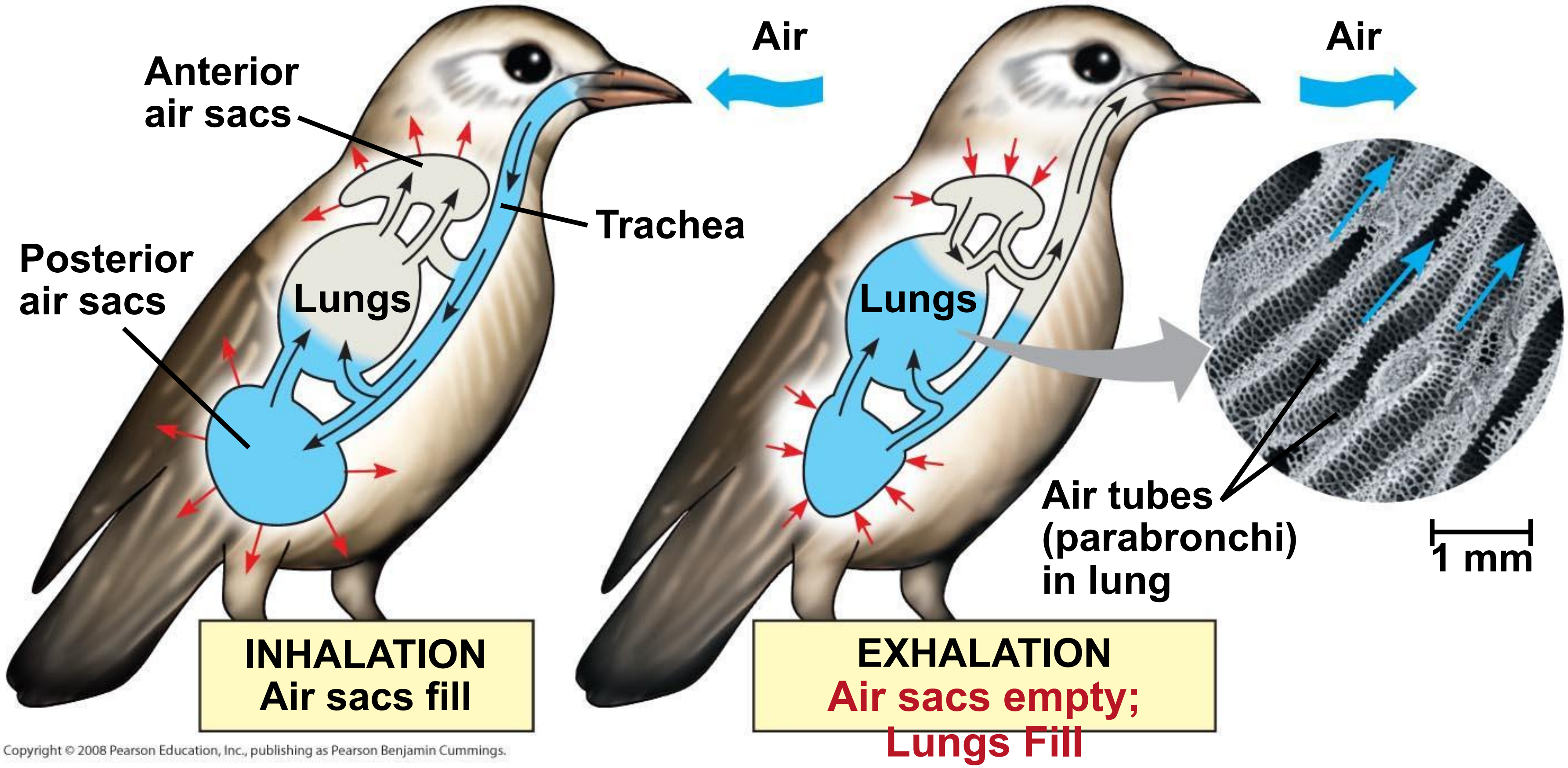
Volume decreases

Pressure

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*.

The Avian Respiratory System

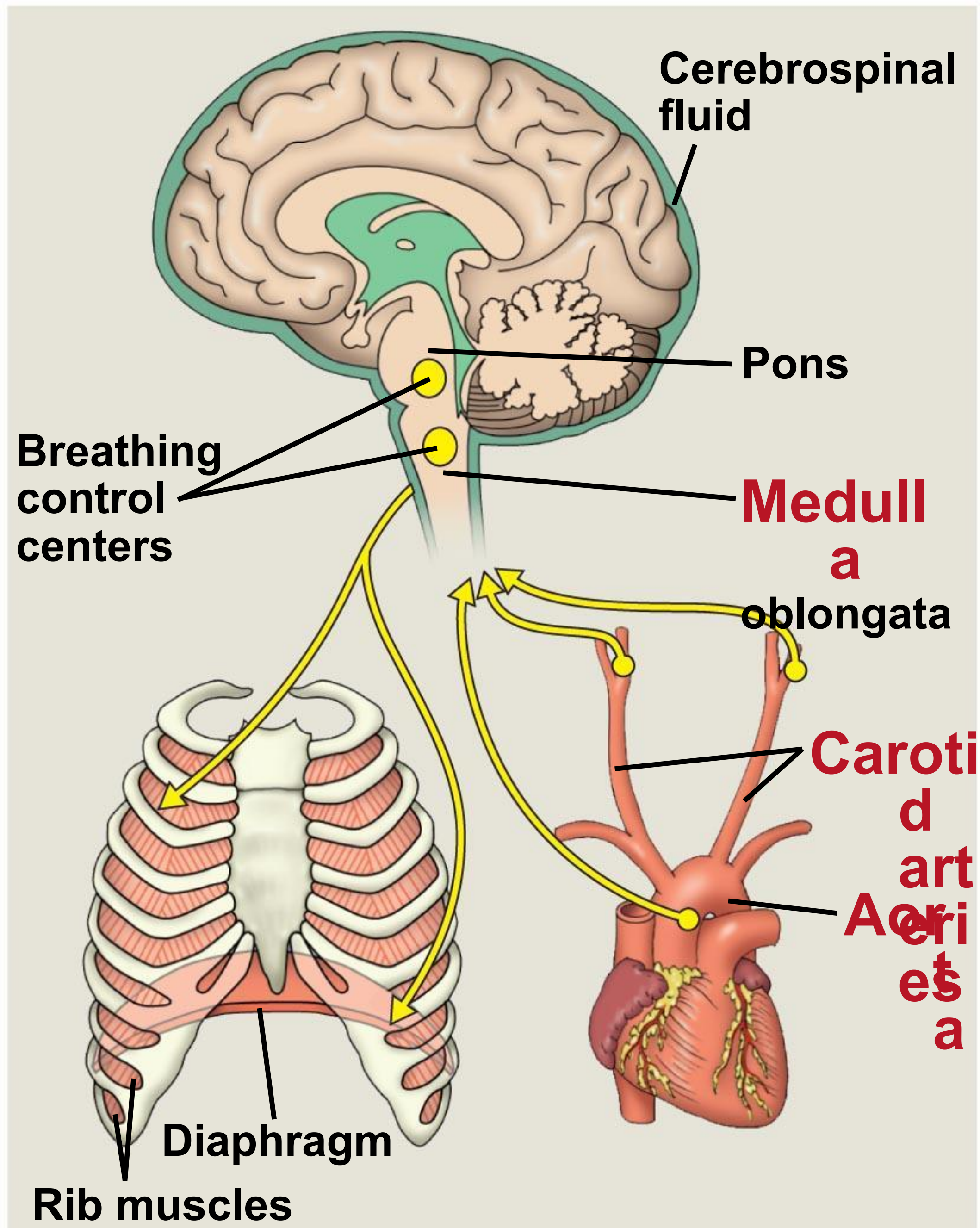


Control of Breathing in Humans

- 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*** - ***CO_2*** levels 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.

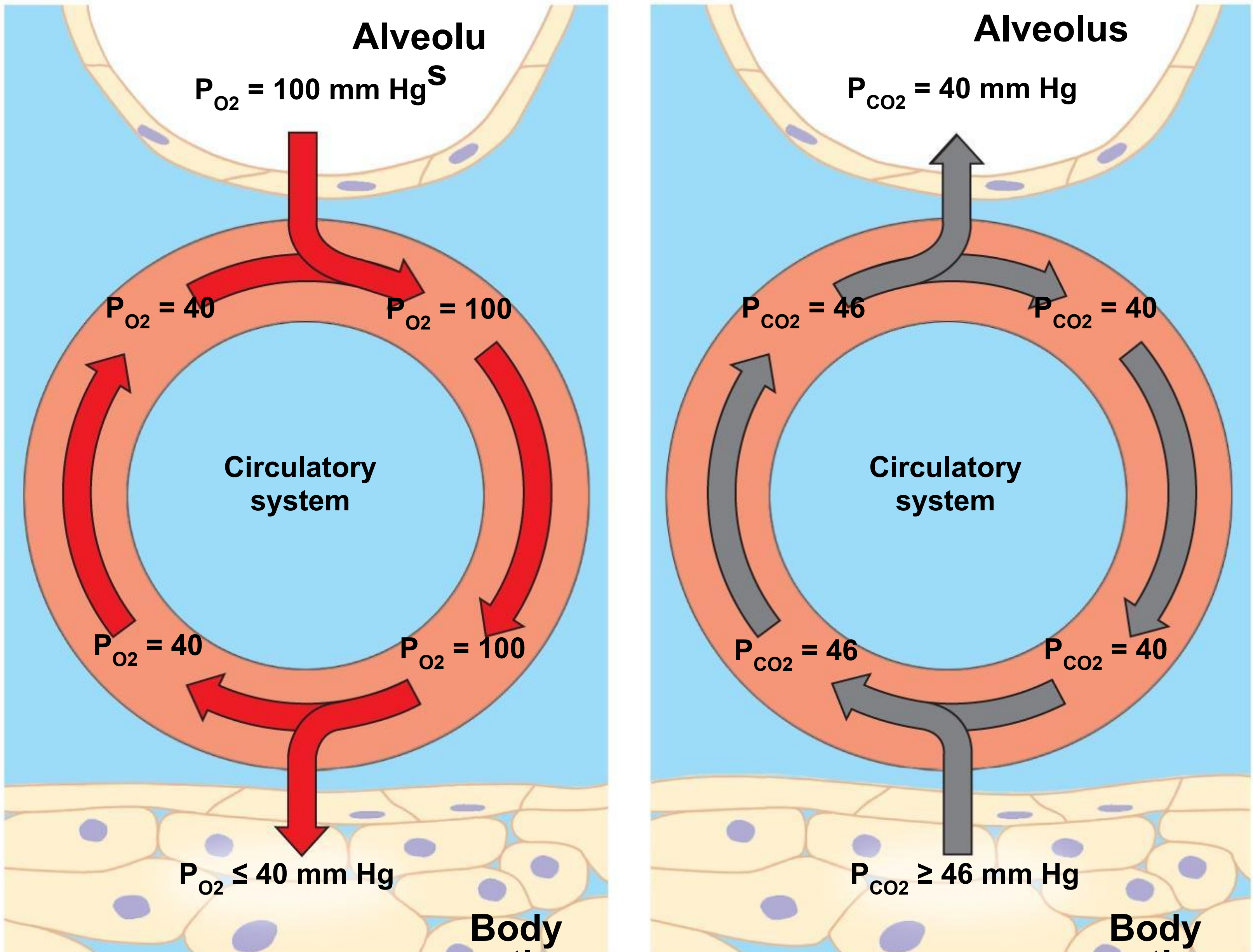
Automatic control of breathing



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
- 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.

Loading and unloading of respiratory gases



(a) Oxy

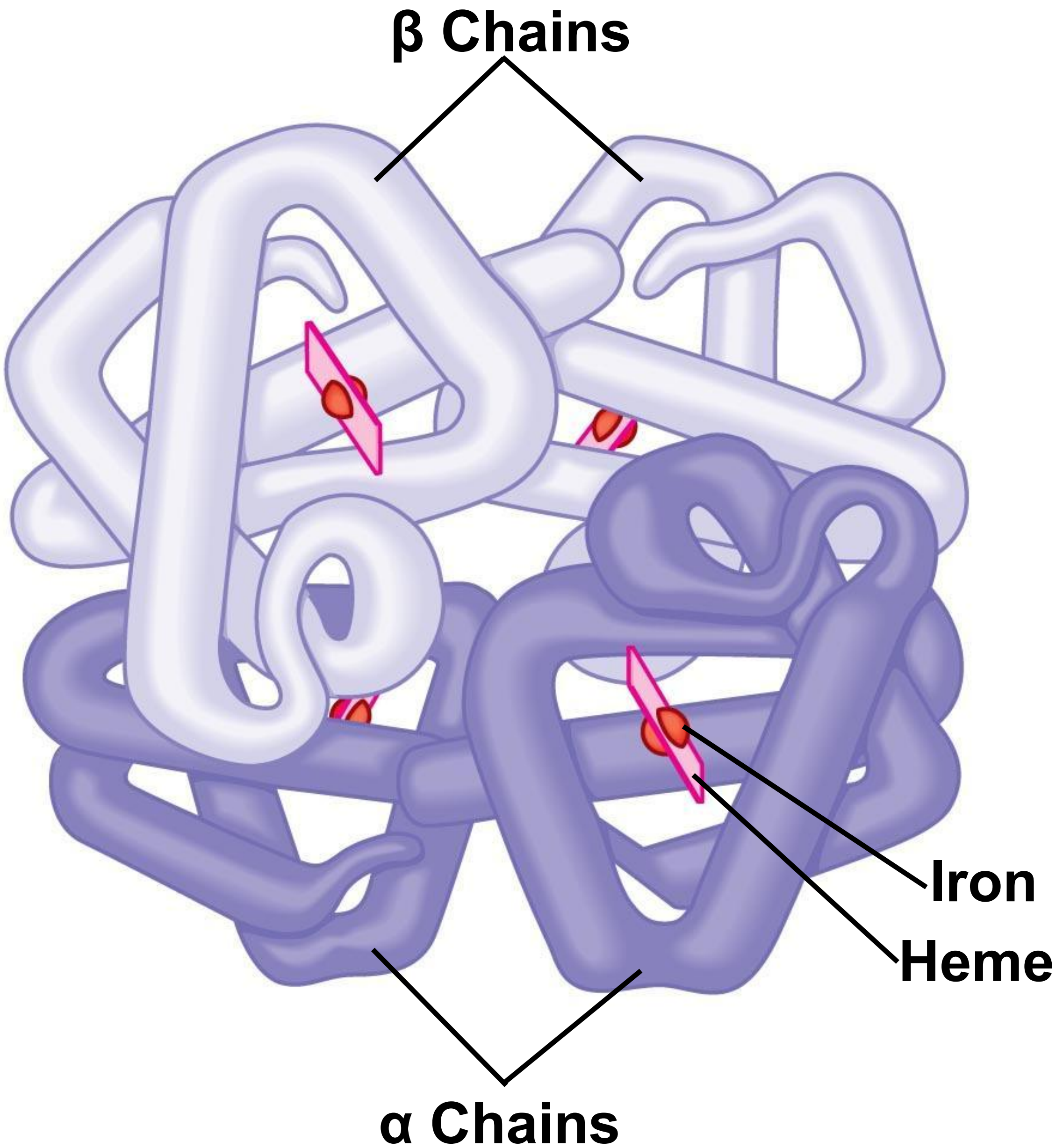
(b) Carbon dioxide

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 with iron = oxygen-binding component contained within erythrocytes.

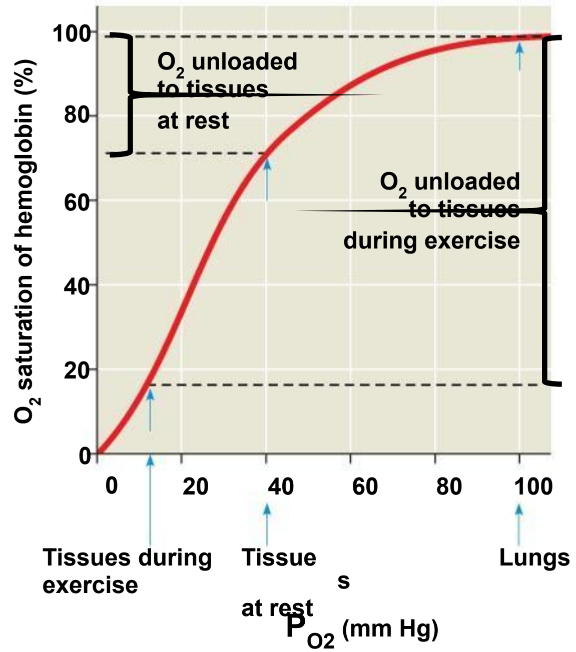
Hemoglobin

- A single hemoglobin molecule can carry four molecules of O_2
- 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***.

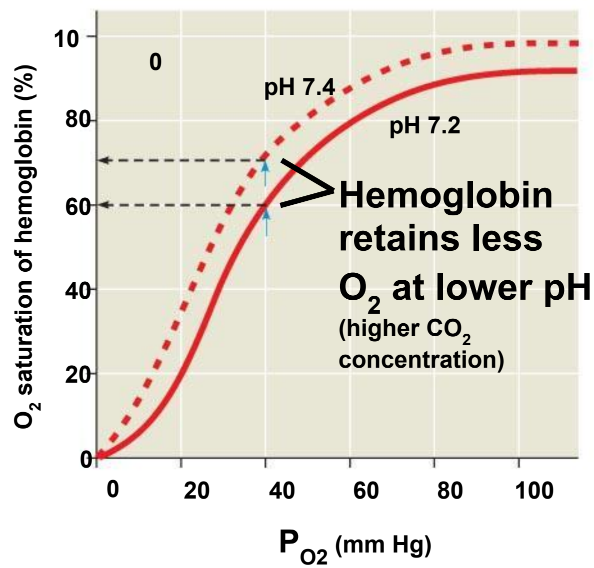


Hemoglob
in

Dissociation curves for hemoglobin at 37ºC



(a) P_{O2} and hemoglobin dissociation at pH 7.4

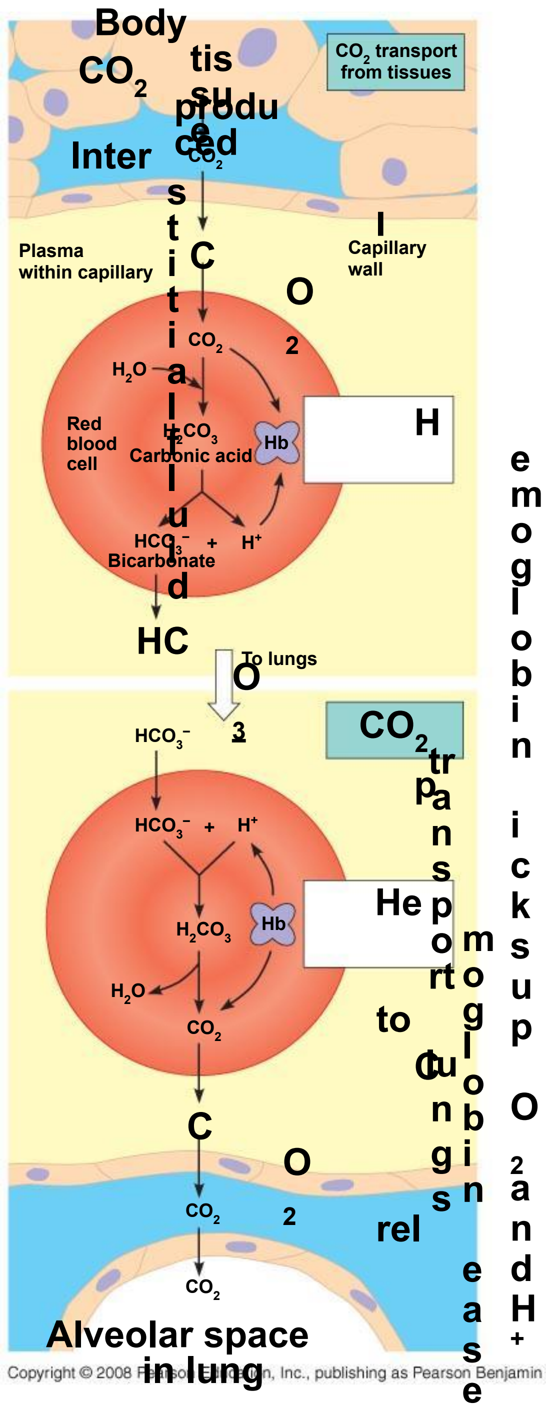


(b) pH and hemoglobin dissociation

Carbon Dioxide Transport

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

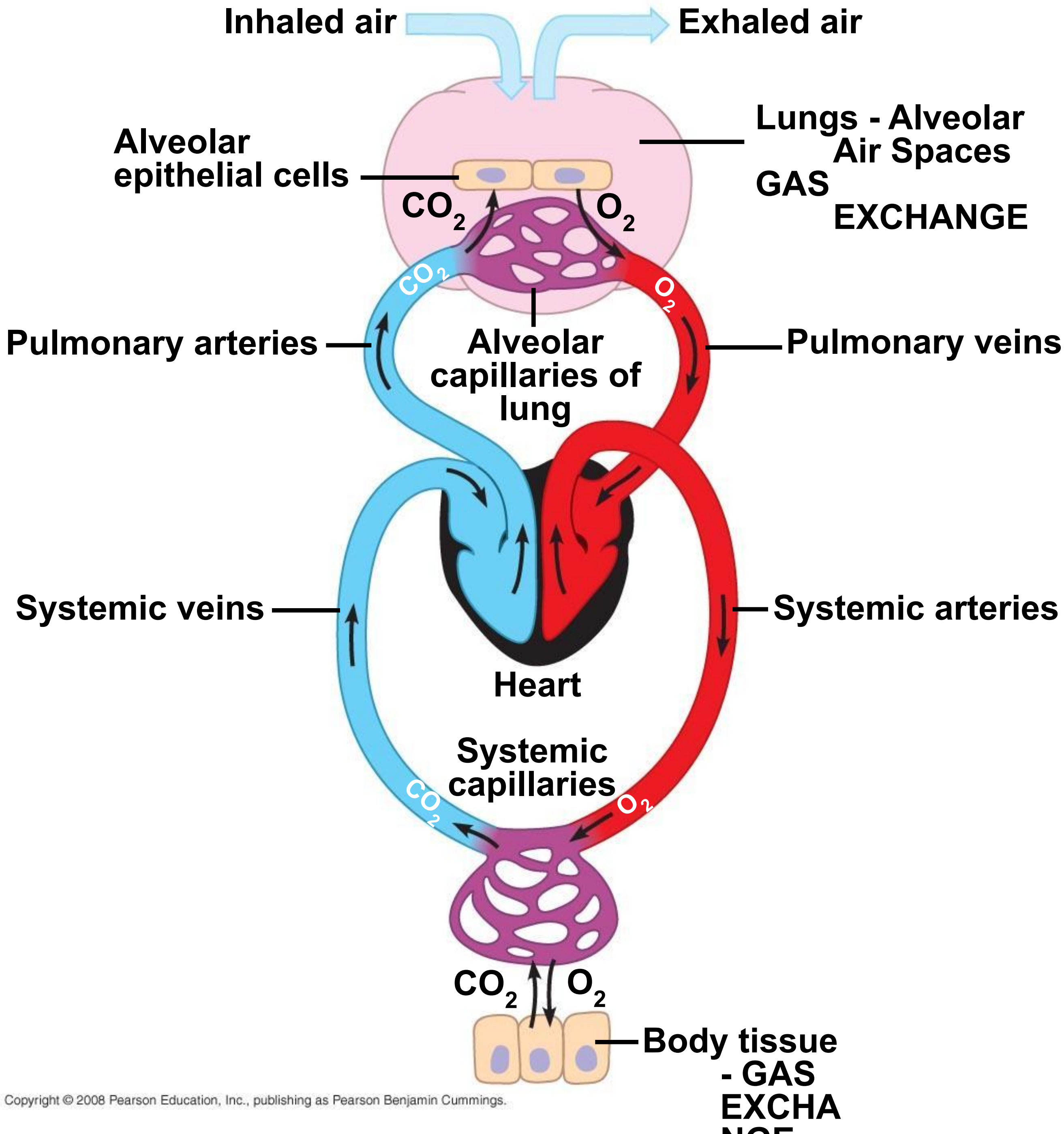
Carbon dioxide transport in the blood



Elite Animal Athletes

- Migratory and diving mammals have evolutionary adaptations that allow them to perform extraordinary feats.
- The extreme O_2 consumption of the antelope-like pronghorn underlies its ability to run at high speed over long distances.
- Deep-diving air breathers stockpile O_2 and deplete it slowly.
- Weddell seals have a high blood to body volume ratio and can store oxygen in their muscles in **myoglobin** proteins.

Review


Inhaled air
Exhaled air
Lungs - Alveolar Air Spaces
GAS EXCHANGE
Alveolar epithelial cells
CO_2
O_2
CO_2
O_2
Pulmonary arteries
Alveolar capillaries of lung
Pulmonary veins
Systemic veins
Systemic arteries
Heart
Systemic capillaries
CO_2
O_2
CO_2
O_2
Body tissue - GAS EXCHA

You should now be able to:

1. Compare and contrast open and closed circulatory systems.
2. Compare and contrast the circulatory systems of fish, amphibians, reptiles, and mammals or birds.
3. Distinguish between pulmonary and systemic circuits and explain the function of each.
4. Trace the path of a red blood cell through the human heart, pulmonary circuit, and systemic circuit.

5. Define cardiac cycle and explain the role of the sinoatrial node.
6. Relate the structures of capillaries, arteries, and veins to their function.
7. Define blood pressure and cardiac output and describe two factors that influence each.
8. Explain how osmotic pressure and hydrostatic pressure regulate the exchange of fluid and solutes across the capillary walls.

9. Describe the role played by the lymphatic system in relation to the circulatory system.

0. Describe the function of erythrocytes, leukocytes, platelets, fibrin.

11. Distinguish between a heart attack and stroke.

2. Discuss the advantages and disadvantages of water and of air as respiratory media.

13. For humans, describe the exchange of gases in the lungs and in tissues.

14. Draw and explain the hemoglobin-oxygen dissociation curve.