Circulatory and Respiratory Systems
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:
  – $\text{O}_2$ diffuses from the water into blood vessels.
  – $\text{CO}_2$ diffuses from blood into the water.

• Internal transport and gas exchange are functionally related in most animals.
Circulatory systems link exchange surfaces with cells throughout the body

• 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
(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.
Figure 42.3

(a) An open circulatory system

Heart

Hemolymph in sinuses surrounding organs

Pores

Tubular heart

(b) A closed circulatory system

Heart

Interstitial fluid

Blood

Small branch vessels in each organ

Dorsal vessel (main heart)

Auxiliary hearts

Ventral vessels
• 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
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** 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
  - **Veins** return blood from capillaries to the heart
Figure 42.4

(a) Single circulation

(b) Double circulation

Key
- Red: Oxygen-rich blood
- Blue: Oxygen-poor blood

Systemic circuit

Pulmonary circuit

Body capillaries

Gill capillaries

Artery

Heart:
Atrium (A)
Ventricle (V)

Vein

Lung capillaries

Right

A

V

Left

A

V

Systemic capillaries

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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
  - 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
• 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
• When underwater, blood flow to the lungs is nearly shut off
Amphibians

Pulmocutaneous circuit

Lung and skin capillaries

Atrium (A)

Right

Left

Ventricle (V)

Systemic capillaries

Systemic circuit

Key

- Red: Oxygen-rich blood
- Blue: 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)

Pulmonary circuit

Lung capillaries

Right systemic aorta

Left systemic aorta

Incomplete septum

Systemic capillaries

Systemic circuit

Key

- Red: Oxygen-rich blood
- Blue: Oxygen-poor blood
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

Pulmonary circuit

Lung capillaries

Atrium (A)

Ventricle (V)

Right

Left

Systemic circuit

Systemic capillaries

Key

- Oxygen-rich blood
- Oxygen-poor blood
Figure 42.5

**Amphibians**

- Pulmocutaneous circuit
- Pulmonary circuit
- Lung and skin capillaries
- Atrium (A)
- Right systemic aorta
- Left systemic aorta
- Systemic capillaries

**Reptiles (Except Birds)**

- Pulmonary circuit
- Lung capillaries
- Right systemic aorta
- Left systemic aorta
- Incomplete septum
- Systemic capillaries

**Mammals and Birds**

- Pulmonary circuit
- Lung capillaries
- Incomplete septum
- Systemic capillaries

**Key**

- Oxygen-rich blood
- Oxygen-poor blood

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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
Animation: Path of Blood Flow in Mammals
Right-click slide / select “Play”
Figure 42.6

Superior vena cava

Pulmonary artery

Capillaries of right lung

Pulmonary vein

Right atrium

Right ventricle

Inferior vena cava

Aorta

Pulmonary artery

Capillaries of left lung

Pulmonary vein

Left atrium

Left ventricle

Capillaries of abdominal organs and hind limbs
Maintaining the Heart’s Rhythmic Beat

- Some cardiac muscle cells are self-excitatory, 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).
SA node (pacemaker)

ECG
SA node (pacemaker)

AV node

ECG

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SA node (pacemaker)

AV node

Bundle branches

Heart apex

Purkinje fibers
• 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
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
Blood pressure reading: 120/70

1. Artery closed
2. Sounds audible in stethoscope
3. Sounds stop

Figure 42.12
Figure 42.15 INTERSTITIAL FLUID

Net fluid movement out

Blood pressure

Osmotic pressure

Arterial end of capillary

Direction of blood flow

Venous end of capillary

Body cell

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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
Figure 42.17

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Major functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>Solvent for carrying other substances</td>
</tr>
<tr>
<td>Ions (blood electrolytes)</td>
<td>Osmotic balance, pH buffering, and regulation of membrane permeability</td>
</tr>
<tr>
<td>Sodium</td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td></td>
</tr>
<tr>
<td>Calcium</td>
<td></td>
</tr>
<tr>
<td>Magnesium</td>
<td></td>
</tr>
<tr>
<td>Chloride</td>
<td></td>
</tr>
<tr>
<td>Bicarbonate</td>
<td></td>
</tr>
<tr>
<td>Plasma proteins</td>
<td>Osmotic balance, pH buffering</td>
</tr>
<tr>
<td>Albumin</td>
<td></td>
</tr>
<tr>
<td>Fibrinogen</td>
<td>Clotting</td>
</tr>
<tr>
<td>Immunoglobulins (antibodies)</td>
<td>Defense</td>
</tr>
<tr>
<td>Substances transported by blood</td>
<td></td>
</tr>
<tr>
<td>Nutrients</td>
<td></td>
</tr>
<tr>
<td>Waste products</td>
<td></td>
</tr>
<tr>
<td>Respiratory gases</td>
<td></td>
</tr>
<tr>
<td>Hormones</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cell type</th>
<th>Number per $\text{mL} (\text{mm}^3)$ of blood</th>
<th>Functions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leukocytes (white blood cells)</td>
<td>5,000–10,000</td>
<td>Defense and immunity</td>
</tr>
<tr>
<td>Basophils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lymphocytes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eosinophils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Neutrophils</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monocytes</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Platelets</td>
<td>250,000–400,000</td>
<td>Blood clotting</td>
</tr>
<tr>
<td>Erythrocytes (red blood cells)</td>
<td>5–6 million</td>
<td>Transport of $\text{O}_2$ and some $\text{CO}_2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 in Aquatic Animals

• Gills are outfoldings of the body that create a large surface area for gas exchange
Figure 42.22

(a) Marine worm
Parapodium (functions as gill)

(b) Crayfish
Gills

(c) Sea star
Coelom
"Tube foot"
• **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 O₂ than the water it meets
Figure 42.23

Gill arch

O$_2$-poor blood

O$_2$-rich blood

Blood vessels

Gill arch

Water flow

Operculum

Lamella

Blood flow

Countercurrent exchange

P$_{O_2}$ (mm Hg) in water

P$_{O_2}$ (mm Hg) in blood

Net diffusion of O$_2$
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
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

- Pharynx
- Larynx (Esophagus)
- Trachea
- Right lung
- Bronchus
- Bronchiole
- Diaphragm
- Branch of pulmonary vein (oxygen-rich blood)
- Terminal bronchiole
- Nasal cavity
- Left lung
- Capillaries
- Alveoli
- 50 μm
- 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
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

1. Rib cage expands.
   - Air inhaled.
   - Lung
   - Diaphragm

2. Rib cage gets smaller.
   - Air exhaled.
• 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.
- Sensors in the aorta and carotid arteries monitor $O_2$ and $CO_2$ concentrations in the blood.
- These sensors exert secondary control over breathing.
Homeostasis: Blood pH of about 7.4

CO₂ level decreases.

Stimulus: Rising level of CO₂ in tissues lowers blood pH.

Response: Rib muscles and diaphragm increase rate and depth of ventilation.

Sensor/control center: Cerebrospinal fluid

Medulla oblongata

Carotid arteries

Aorta
(a) The path of respiratory gases in the circulatory system
CO₂ transport from tissues

Body tissue

CO₂ produced

Interstitial fluid

CO₂

Plasma within capillary

Capillary wall

Hemoglobin (Hb) picks up CO₂ and H⁺.

Red blood cell

H₂CO₃

Carbonic acid

H₂O

H₂CO₃

Bicarbonate

H⁺

HCO₃⁻

HCO₃⁻

To lungs