

## CHAPTER 2. CIRCULATORY SYSTEM

### **The circulatory system**

The circulatory system is the animal body's transport network. It moves respiratory gases, nutrients, hormones, heat, immune cells, and metabolic wastes between organs, helping maintain internal stability (**homeostasis**). In simple animals, diffusion can be enough; in larger or more active animals, a specialized circulatory system is needed because diffusion alone is too slow over long distances.

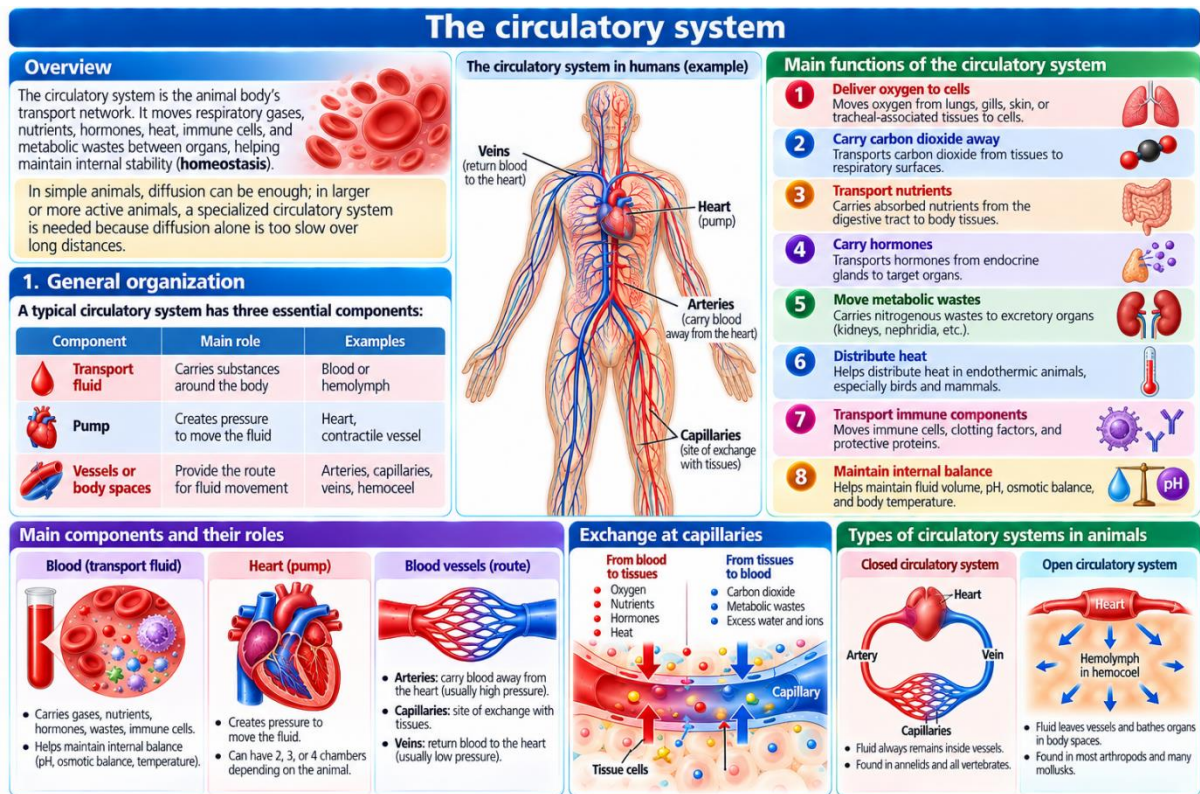
### **1. General organization**

A typical circulatory system has three essential components:

| Component              | Main role                            | Examples                               |
|------------------------|--------------------------------------|----------------------------------------|
| Transport fluid        | Carries substances around the body   | Blood or hemolymph                     |
| Pump                   | Creates pressure to move the fluid   | Heart, contractile vessel              |
| Vessels or body spaces | Provide the route for fluid movement | Arteries, capillaries, veins, hemocoel |

**The main functions are:**

- Deliver oxygen from lungs, gills, skin, or tracheal-associated tissues to cells.
- Carry carbon dioxide away from tissues to respiratory surfaces.
- Transport absorbed nutrients from the digestive tract.
- Carry hormones from endocrine glands to target organs.
- Move nitrogenous wastes to excretory organs.
- Distribute heat in endothermic animals, especially birds and mammals.
- Transport immune cells, clotting factors, and protective proteins.
- Maintain fluid volume, pH, osmotic balance, and body temperature.



## 2. Open versus closed systems

### Open circulatory system

In an **open circulatory system**, the pumping fluid—usually called *hemolymph*—is not always confined to blood vessels. The heart pumps hemolymph into body spaces called the hemocoel, where it bathes organs directly before returning to the heart.

This system occurs in most arthropods, such as insects, spiders, and crustaceans, and in many mollusks.

#### Advantages

- Structurally simple.
- Requires relatively low pressure.
- Energy cost is generally lower.

#### Limitations

- Fluid distribution is slower and less precisely controlled.
- It is less effective for rapid delivery of oxygen in large, highly active animals.

Insects are a useful exception: their circulatory system does not usually transport much oxygen, because oxygen reaches tissues directly through the tracheal system.

### Closed circulatory system

In a **closed circulatory system**, blood remains inside vessels and is separated from the interstitial fluid surrounding cells. Exchange occurs mainly through capillary walls. This design is found in all vertebrates and in some invertebrates, including annelids such as earthworms and cephalopod mollusks such as octopuses.

#### Advantages

- Higher pressure and faster blood flow.
- More efficient delivery of oxygen and nutrients.
- Blood can be directed selectively to organs with high demand, such as muscles during exercise or the digestive tract after feeding.
- Well suited to large, active animals.

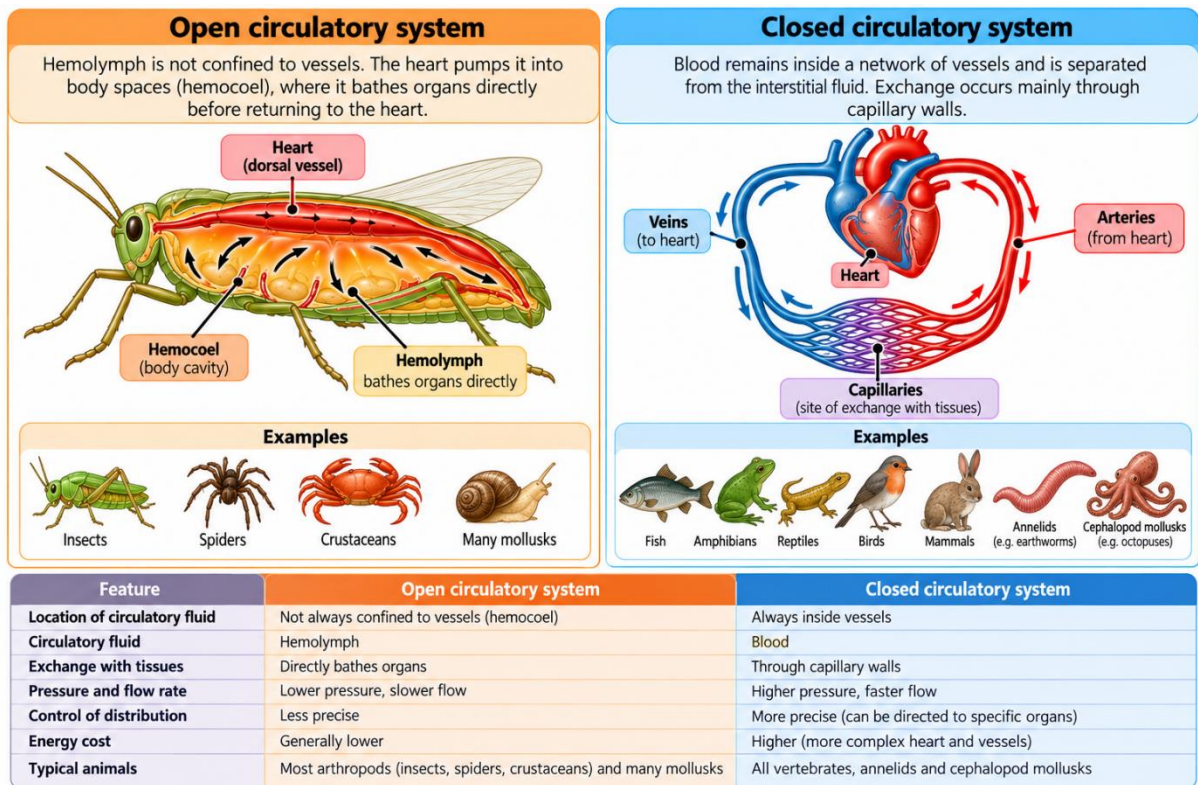
#### **Limitation**

- It requires a more complex heart and vessel network.

### **3. Evolution of circulation**

The complexity of circulation generally increased as animals became larger, more active, and metabolically demanding.

| <b>Animal group</b>            | <b>Main pattern</b>                                                                      |
|--------------------------------|------------------------------------------------------------------------------------------|
| Sponges, cnidarians, flatworms | No true circulatory system; diffusion or gastrovascular cavity distributes materials     |
| Annelids                       | Closed circulation, often with dorsal and ventral vessels                                |
| Arthropods                     | Usually open circulation with hemolymph                                                  |
| Most mollusks                  | Open circulation                                                                         |
| Cephalopods                    | Closed circulation; supports active predatory life                                       |
| Fish                           | Closed, single circulation                                                               |
| Amphibians and most reptiles   | Closed, double circulation with partial separation of blood                              |
| Birds and mammals              | Closed, double circulation with complete separation of oxygenated and deoxygenated blood |



## 4. Blood and hemolymph

### Blood

Blood is a connective tissue composed of plasma and cells.

| Blood component                | Function                                                                      |
|--------------------------------|-------------------------------------------------------------------------------|
| Plasma                         | Liquid medium carrying water, ions, nutrients, hormones, proteins, and wastes |
| Red blood cells / erythrocytes | Transport oxygen, mainly using hemoglobin                                     |
| White blood cells / leukocytes | Immune defense                                                                |
| Platelets or thrombocytes      | Blood clotting and repair of damaged vessels                                  |

In mammals, mature red blood cells lack nuclei, creating more space for hemoglobin. In birds, reptiles, amphibians, and fish, erythrocytes are usually nucleated.

### Hemolymph

Hemolymph is the fluid in many animals with open circulation. It may transport nutrients, hormones, wastes, and immune cells. Its role in oxygen transport varies by species:

- In insects, hemolymph usually does not carry much oxygen.
- In many crustaceans and mollusks, hemolymph contains respiratory pigments such as hemocyanin, which contains copper and can appear blue when oxygenated.

## **5. Blood vessels**

In vertebrates, blood travels through a continuous network of vessels.

### **Arteries**

Arteries carry blood **away from the heart**.

- They have thick, elastic, muscular walls.
- They withstand relatively high pressure.
- Most systemic arteries carry oxygen-rich blood.
- The pulmonary artery is an important exception: it carries oxygen-poor blood from the right ventricle to the lungs.

### **Arterioles**

Arterioles are small arteries that regulate blood flow into capillary beds.

Their smooth muscle can contract (**vasoconstriction**) or relax (**vasodilation**). By changing their diameter, arterioles strongly influence resistance, blood pressure, and blood distribution to tissues.

### **Capillaries**

Capillaries are the smallest vessels and have walls only one cell thick.

They are the principal sites of exchange:

- Oxygen moves from blood to tissues.
- Carbon dioxide moves from tissues to blood.
- Nutrients move into cells.
- Wastes move from cells into blood.
- Water and dissolved substances move between plasma and interstitial fluid.

### **Veins**

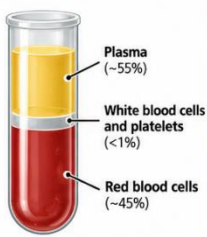
Veins carry blood **toward the heart**.

- They operate at lower pressure than arteries.
- Their walls are thinner and less muscular.
- Many veins contain valves that prevent backflow.
- Skeletal muscle contractions help return blood to the heart; this is called the skeletal-muscle pump.

Most systemic veins carry oxygen-poor blood. The pulmonary veins are the exception: they transport oxygen-rich blood from the lungs to the left atrium.

### 4 Blood and hemolymph (vertebrates)

**Blood** (vertebrates) Blood is a connective tissue composed of plasma and cells.



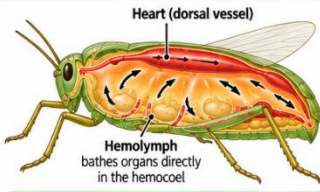
| Component                             | Function                                                       |
|---------------------------------------|----------------------------------------------------------------|
| <b>Plasma</b> (liquid medium)         | Carries water, ions, nutrients, hormones, proteins and wastes. |
| <b>Red blood cells</b> (erythrocytes) | Transport oxygen, mainly using hemoglobin.                     |
| <b>White blood cells</b> (leukocytes) | Immune defense.                                                |
| <b>Platelets</b> (thrombocytes)       | Blood clotting and repair of damaged vessels.                  |

**Mammals:** mature red blood cells lack nuclei, creating more space for hemoglobin.  **Mammal** (RBC without nucleus)

**Birds, reptiles, amphibians and fish:** erythrocytes are usually nucleated.  **Bird/reptile/amphibian/fish** (RBC with nucleus)

### Hemolymph (invertebrates with open circulation)

Hemolymph is the fluid in many animals with open circulation. It may transport nutrients, hormones, wastes, and immune cells. Its role in oxygen transport varies by species.



**Heart (dorsal vessel)**

**Hemolymph** bathes organs directly in the hemocoel

**Functions**

- Transport nutrients, hormones, wastes and immune cells.
- Role in oxygen transport varies by species.

**Examples and oxygen transport**

**Insects**



- Hemolymph usually does not carry much oxygen.
- Oxygen reaches tissues directly through the tracheal system.

**Crustaceans and many mollusks**



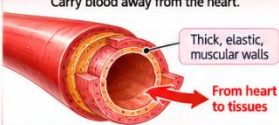
- Hemolymph contains respiratory pigments such as hemocyanin (copper-based).
- Can appear blue when oxygenated.

### 5 Blood vessels (vertebrates)

In vertebrates, blood travels through a continuous network of vessels.

**Arteries**

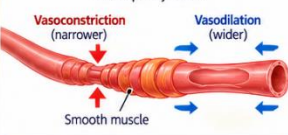
Carry blood away from the heart.



- Thick, elastic, muscular walls.
- Withstand relatively high pressure.
- Most systemic arteries carry oxygen-rich blood.
- Pulmonary artery is an exception: carries oxygen-poor blood from the right ventricle to the lungs.

**Arterioles**

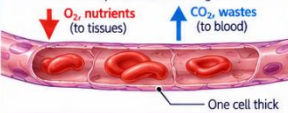
Small arteries that regulate blood flow into capillary beds.



- Their smooth muscle can contract (vasoconstriction) or relax (vasodilation).
- By changing their diameter, arterioles influence resistance, blood pressure, and blood distribution to tissues.

**Capillaries**

Smallest vessels; walls only one cell thick. Principal sites of exchange.

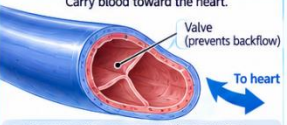


**Exchange:**

- Oxygen moves from blood to tissues.
- Carbon dioxide moves from tissues to blood.
- Nutrients move into cells.
- Wastes move from cells into blood.
- Water and dissolved substances move between plasma and interstitial fluid.

**Veins**

Carry blood toward the heart.



- Operate at lower pressure than arteries.
- Walls are thinner and less muscular.
- Many veins contain valves that prevent backflow.
- Skeletal muscle contractions help return blood to the heart (skeletal-muscle pump).
- Most systemic veins carry oxygen-poor blood.
- Pulmonary veins are an exception: transport oxygen-rich blood from the lungs to the left atrium.

## 6. The vertebrate heart

The heart is a muscular pump. In mammals and birds, it works as two pumps in series:

- The right side sends oxygen-poor blood to the lungs.
- The left side sends oxygen-rich blood to the body.

The heart has four chambers:

| Chamber         | Main function                             |
|-----------------|-------------------------------------------|
| Right atrium    | Receives oxygen-poor blood from the body  |
| Right ventricle | Pumps oxygen-poor blood to the lungs      |
| Left atrium     | Receives oxygen-rich blood from the lungs |
| Left ventricle  | Pumps oxygen-rich blood to the whole body |

The left ventricle has the thickest muscular wall because it must generate enough pressure to send blood throughout the systemic circulation.

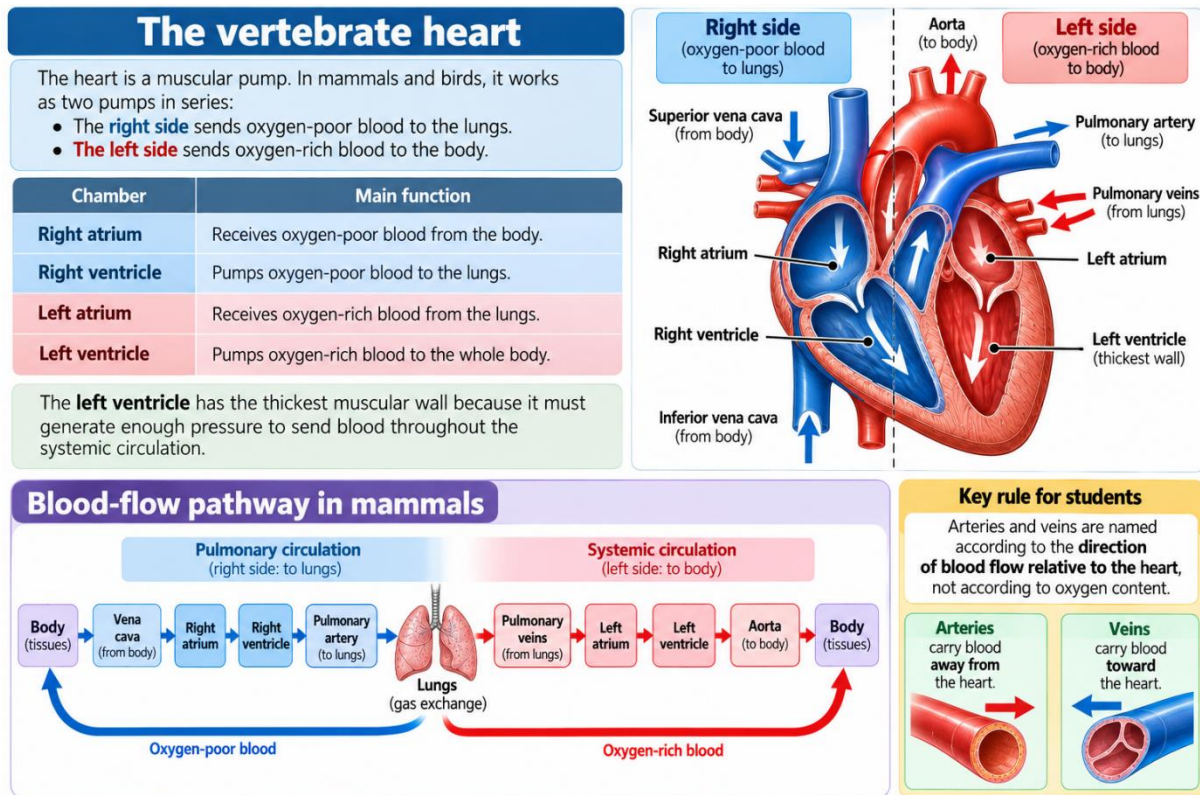
### Blood-flow pathway in mammals

Body→vena cava→right atrium→right ventricle

→pulmonary artery→lungs→pulmonary veins

→left atrium→left ventricle→aorta→body→left atrium→left ventricle→aorta→body

A key rule for students: arteries and veins are named according to the **direction of blood flow relative to the heart**, not according to oxygen content.



## 7. Single and double circulation

### Single circulation: fish

Fish have a two-chambered heart: one atrium and one ventricle. Blood passes through the heart once during each complete circuit.

Heart→gills→body tissues→heartHeart→gills→body tissues→heart

At the gills, blood gains oxygen. However, blood pressure falls after passing through gill capillaries, so flow to the body is relatively less forceful than in animals with double circulation.

### Double circulation: tetrapods

Amphibians, reptiles, birds, and mammals have two circuits:

- **Pulmonary circuit:** heart → lungs → heart
- **Systemic circuit:** heart → body → heart

Double circulation allows blood to return to the heart after the respiratory surface and be pumped again at high pressure to body tissues.

**Fig. Cardiovascular and lymphatic circulation diagram**

### Comparison among vertebrates

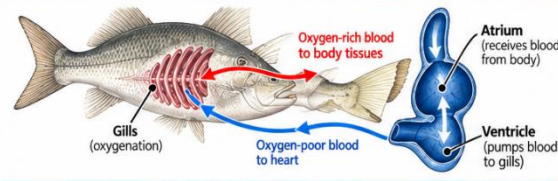
| Group         | Heart chambers        | Circulation | Mixing of oxygenated and deoxygenated blood                          |
|---------------|-----------------------|-------------|----------------------------------------------------------------------|
| Fish          | 2                     | Single      | No mixing in the heart because it receives mainly deoxygenated blood |
| Amphibians    | 3                     | Double      | Some mixing in one ventricle                                         |
| Most reptiles | 3 with partial septum | Double      | Limited mixing                                                       |
| Crocodylians  | 4                     | Double      | Complete anatomical separation, with specialized shunting capability |
| Birds         | 4                     | Double      | Complete separation                                                  |
| Mammals       | 4                     | Double      | Complete separation                                                  |

Birds and mammals have complete separation of oxygen-rich and oxygen-poor blood, supporting high metabolic rates, sustained activity, and endothermy.

### 7. Single and double circulation

#### Single circulation: fish

Fish have a two-chambered heart (one atrium and one ventricle). Blood passes through the heart once during each complete circuit.



##### Pathway of blood flow in fish (single circulation)

```

graph LR
    Heart["Heart (2 chambers: 1 atrium, 1 ventricle)"] --> Gills["Gills (blood gains oxygen)"]
    Gills --> BodyTissues["Body tissues (delivers oxygen)"]
    BodyTissues --> Heart
  
```

Blood passes through the heart once per complete circuit.

##### Key points

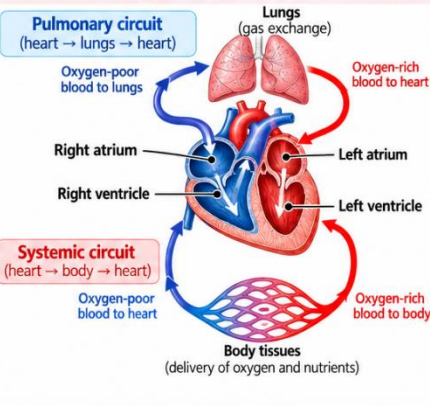
- Blood gains oxygen at the gills.
- Blood pressure falls after passing through gill capillaries, so flow to the body is relatively less forceful than in animals with double circulation.

#### Double circulation: tetrapods

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- **Pulmonary circuit:** heart → lungs → heart
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Double circulation allows blood to return to the heart after the respiratory surface and be pumped again at high pressure to body tissues.



##### Examples (tetrapods)



Amphibians



Reptiles



Birds



Mammals

| Feature                                 | Single circulation (fish)                    | Double circulation (tetrapods)                                                       |
|-----------------------------------------|----------------------------------------------|--------------------------------------------------------------------------------------|
| <b>Heart chambers</b>                   | Two chambers: one atrium and one ventricle   | Four chambers: two atria and two ventricles                                          |
| <b>Number of circuits</b>               | One (heart → gills → body → heart)           | Two (pulmonary and systemic)                                                         |
| <b>Passes through heart per circuit</b> | Once                                         | Twice (once in pulmonary circuit, once in systemic circuit)                          |
| <b>Site of oxygenation</b>              | Gills                                        | Lungs (and skin in amphibians)                                                       |
| <b>Blood pressure to body</b>           | Falls after gill capillaries; relatively low | Higher; blood is pumped again after lungs, allowing a more forceful flow to the body |
| <b>Examples</b>                         | Fish                                         | Amphibians, reptiles, birds, mammals                                                 |

## 8. Cardiac cycle

The **cardiac cycle** is one complete heartbeat. It includes relaxation and contraction of the chambers.

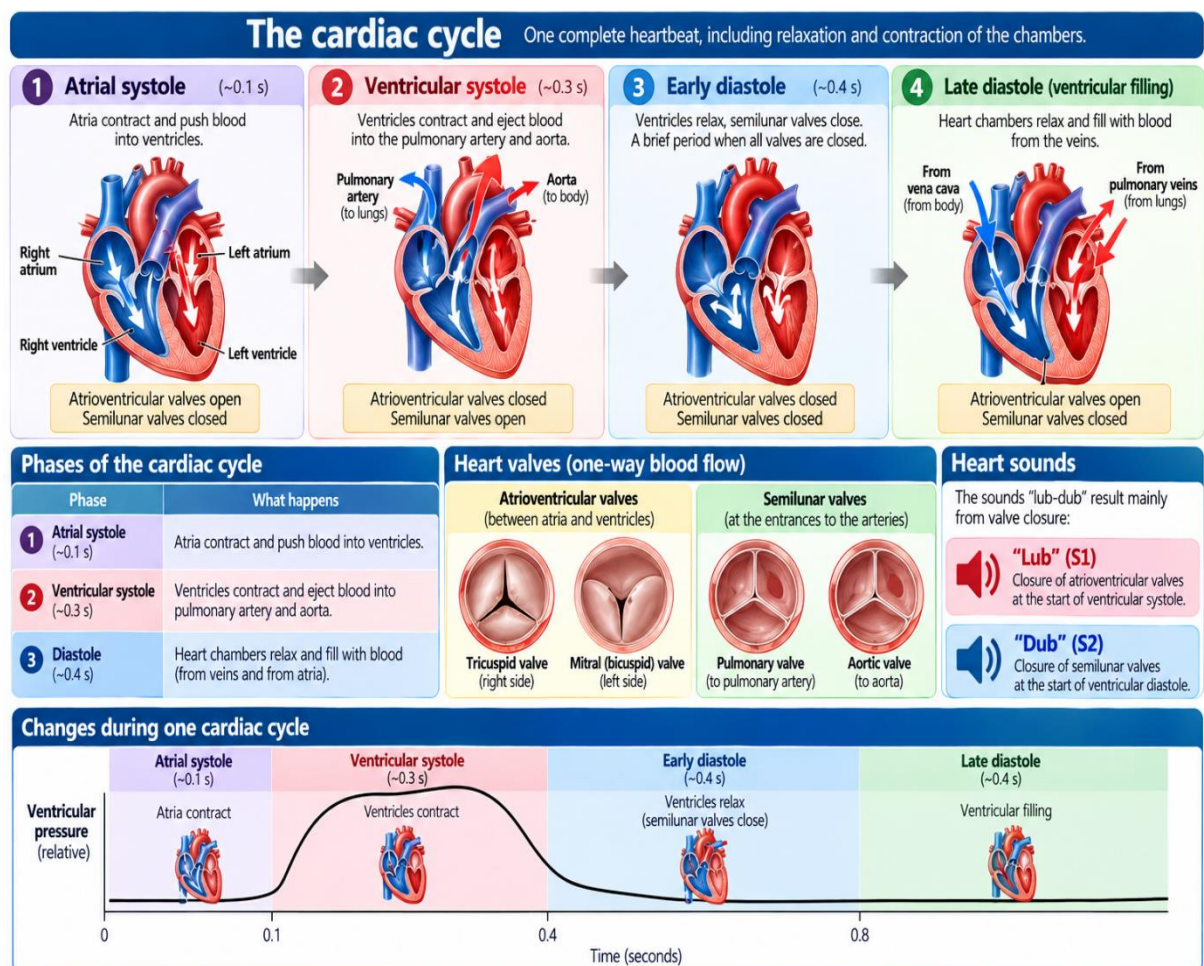
| Phase               | What happens                                                        |
|---------------------|---------------------------------------------------------------------|
| Atrial systole      | Atria contract and push blood into ventricles                       |
| Ventricular systole | Ventricles contract and eject blood into pulmonary artery and aorta |
| Diastole            | Heart chambers relax and fill with blood                            |

The heart valves ensure one-way blood flow:

- Atrioventricular valves lie between atria and ventricles.
- Semilunar valves lie at the entrances to the pulmonary artery and aorta.

The sounds “lub-dub” result mainly from valve closure:

- “Lub”: closure of atrioventricular valves at the start of ventricular systole.
- “Dub”: closure of semilunar valves at the start of ventricular diastole.



## 9. Electrical control of the heart

Cardiac muscle is myogenic in vertebrates: the heart can generate its own rhythmic electrical impulses.

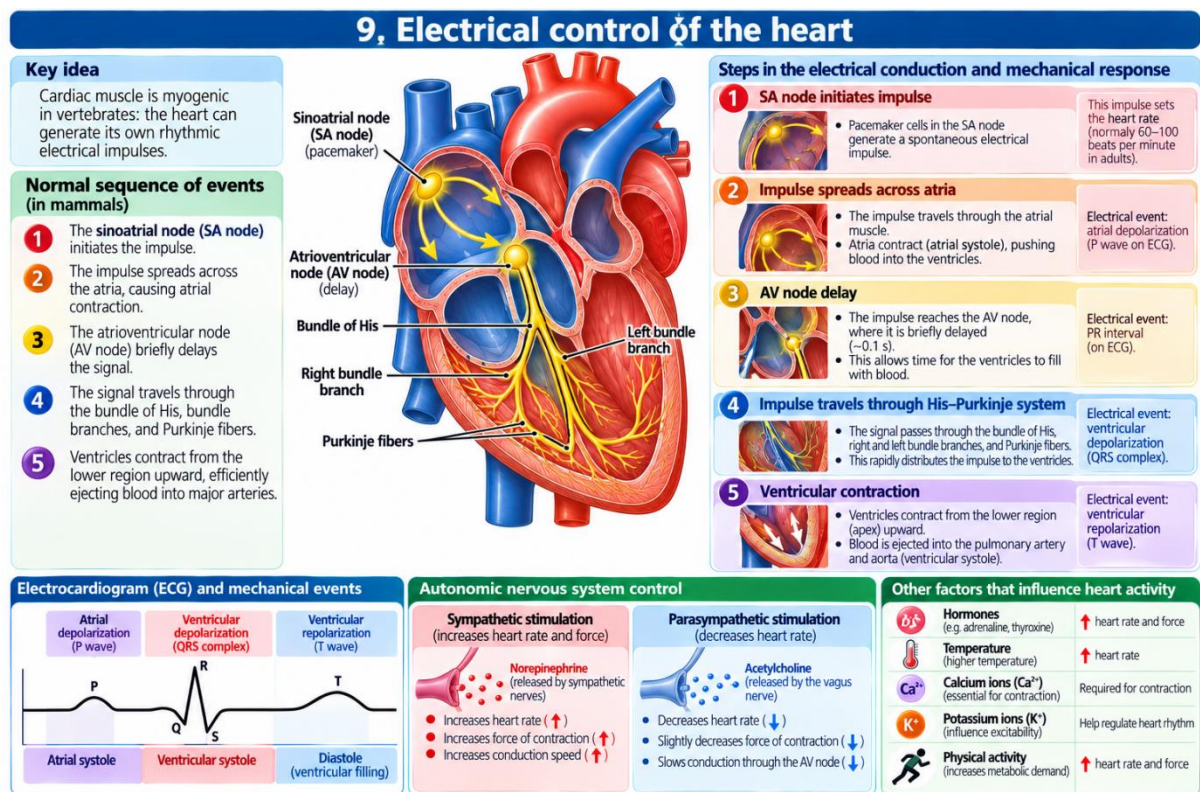
In mammals, the normal sequence is:

1. The sinoatrial node, or **SA node**, initiates the impulse.
2. The impulse spreads across the atria, causing atrial contraction.
3. The atrioventricular node, or **AV node**, briefly delays the signal.
4. The signal travels through the bundle of His, bundle branches, and Purkinje fibers.
5. Ventricles contract from the lower region upward, efficiently ejecting blood into major arteries.

The autonomic nervous system modifies heart rate:

- Sympathetic stimulation increases heart rate and force of contraction.
- Parasympathetic stimulation, mainly via the vagus nerve, decreases heart rate.

Hormones, temperature, ions such as calcium and potassium, and physical activity also influence cardiac activity.



## 10. Regulation of circulation

Circulation must adapt continuously to exercise, rest, digestion, temperature changes, dehydration, blood loss, and stress.

### Local control

Tissues can regulate their own blood supply.

When a tissue is active, it uses more oxygen and produces more carbon dioxide, hydrogen ions, heat, and other metabolites. These local changes often cause vasodilation, increasing blood flow to the active tissue.

Example: during running, skeletal muscles receive much more blood, while blood flow to digestive organs decreases.

### **Nervous control**

The autonomic nervous system regulates heart rate, contractility, and vessel diameter.

- Sympathetic activation supports exercise or “fight-or-flight” responses.
- Parasympathetic activation promotes a lower heart rate during rest.

### **Hormonal control**

Hormones also affect circulation:

- Adrenaline increases cardiac activity and can redirect blood toward skeletal muscle.
- Antidiuretic hormone helps retain water and can support blood pressure.
- The renin–angiotensin–aldosterone system contributes to long-term regulation of blood pressure and blood volume.

## **11. Lymphatic system**

The lymphatic system works closely with the circulatory system.

Its main functions are:

- Return excess interstitial fluid to the bloodstream.
- Return leaked plasma proteins to the circulation.
- Absorb dietary fats from the intestine.
- Provide immune defense through lymph nodes and lymphoid tissues.

If excess fluid is not returned to the blood, it accumulates in tissues and causes edema.

## 10. Regulation of circulation

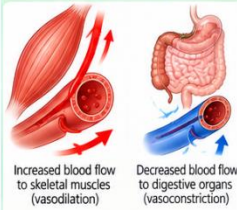
Circulation must adapt continuously to exercise, rest, digestion, temperature changes, dehydration, blood loss, and stress.



### Local control

- Tissues can regulate their own blood supply.
- When a tissue is active, it uses more oxygen and produces more carbon dioxide, hydrogen ions, heat, and other metabolites.
- These local changes often cause **vasodilation**, increasing blood flow to the active tissue.

#### Example: during running



### Nervous control

The autonomic nervous system regulates heart rate, contractility, and vessel diameter.

- Sympathetic activation** supports exercise or "fight-or-flight" responses (increases heart rate and vasoconstriction in many organs, and vasodilation in skeletal muscles).
- Parasympathetic activation** promotes a lower heart rate during rest (mainly via the vagus nerve).

#### Autonomic nervous system effects

| Sympathetic activation                                                                                                                                                                    | Parasympathetic activation                                                                                                              |
|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------|
| <ul style="list-style-type: none"> <li>↑ Heart rate</li> <li>↑ Force of contraction</li> <li>• Vasoconstriction (in many organs)</li> <li>• Vasodilation (in skeletal muscles)</li> </ul> | <ul style="list-style-type: none"> <li>↓ Heart rate</li> <li>↓ Force of contraction</li> <li>↓ Vasodilation (in some organs)</li> </ul> |

### Hormonal control

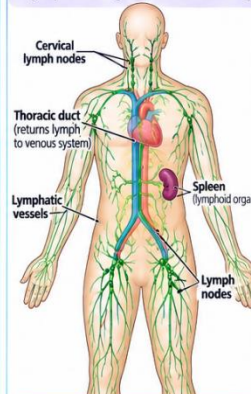
- Hormones also affect circulation.
- Adrenaline** increases cardiac activity and can redirect blood toward skeletal muscle.
- Antidiuretic hormone (ADH)** helps retain water and can support blood pressure.
- The renin-angiotensin-aldosterone system (RAAS)** contributes to long-term regulation of blood pressure and blood volume.

#### Main hormones and effects

|                                                                                                                                                                                                                  |                                                                                                                                                                     |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>Adrenaline</b><br>(from adrenal glands) <ul style="list-style-type: none"> <li>Increases force of contraction</li> <li>Can redirect blood to skeletal muscle</li> </ul>                                       | <b>ADH</b><br>(from posterior pituitary) <ul style="list-style-type: none"> <li>Increases water reabsorption in kidneys</li> <li>Supports blood pressure</li> </ul> |
| <b>Renin-angiotensin-aldosterone system</b><br>(from kidneys) <ul style="list-style-type: none"> <li>Vasoconstriction</li> <li>Increases blood volume</li> <li>Long-term regulation of blood pressure</li> </ul> |                                                                                                                                                                     |

## 11. Lymphatic system

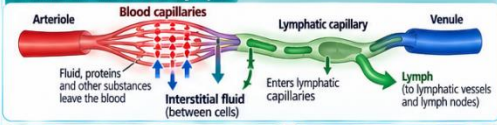
The lymphatic system works closely with the circulatory system. It consists of lymphatic capillaries, vessels, lymph nodes, and lymphoid organs, and returns lymph to the venous bloodstream.



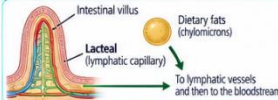
### Main functions

- Return excess interstitial fluid to the bloodstream**  
Collects fluid that has left blood capillaries and returns it to the venous circulation.
- Return leaked plasma proteins**  
Collects and returns plasma proteins to the blood.
- Absorb dietary fats**  
Lacteals in the intestine absorb and transport dietary fats (chylomicrons) to the circulation.
- Provide immune defense**  
Lymph nodes and lymphoid tissues filter lymph and help detect and destroy pathogens.

### Formation and flow of lymph



#### Lymph in the intestine (fat absorption)



#### If lymph is not returned to the blood

