A circulatory system consists of a muscular pump (heart), a circulatory fluid (blood), and a set of tubes or vessels to carry the blood. Two basic types of circulatory systems have evolved in animals:

1. **Open circulatory system** – the system is called “open” because fluid is pumped through open-ended vessels and flows out among the cells; there's is no distinction between blood and interstitial fluid. In an insect, such as the grasshopper in Figure 1.

2. **Closed circulatory system** – The vertebrate circulatory system is often called a cardiovascular system. The blood is confined to vessels, which keep it distinct from the interstitial fluid. There are three kinds of vessels; Arteries carry blood away from the heart to body organs and tissues; veins return blood to the heart; and capillaries convey blood between arteries and veins within each tissue.

   - The cardiovascular system of a fish illustrates key features of a closed circulatory system. The heart of a fish has two main chambers. The atrium receives blood from the veins, and the ventricle pumps blood to the gills via large arteries. The large arteries branch into arterioles, small vessels that give rise to capillaries. Networks of capillaries called capillary beds infiltrate every organ and tissue in the body. The thin walls of the capillaries allow chemical exchange between the blood and the interstitial fluid. The capillaries converge into venules, which in turn converge into veins that return blood to the heart.
Figure 3: A fish has a single circuit of blood flow and two heart chambers. Blood pumped form the ventricle travels first to the gill capillaries. Blood pressure drops considerably while blood passes through the gill capillaries for reasons we will explain shortly, but the blood is helped on its way by the animal's swimming movements. An artery carries the oxygen-rich blood to systemic (body) capillaries in the tissues and organs of the body, from which the blood then returns to the atrium of the heart.

Figure 4: Frogs and other amphibians have a three-chambered heart. The right atrium receives blood returning from the systemic capillaries. The ventricle pumps blood to capillary beds in the lungs and skin. Because gas exchange occurs both in the lungs and across the thin, moist skin, this is called a pulmocutaneous circuit. Oxygen-rich blood returns to the left atrium. Although blood from the left and right atria mixes in the single ventricle, most of the oxygen-poor blood is diverted to the pulmocutaneous circuit and most of the oxygen-rich blood goes to the systemic circuit.

Figure 5: In all birds and mammals, the heart has four chambers: two atria and two ventricles. The right side of the heart handles only oxygen-poor blood, while the left side receives and pumps only oxygen-rich blood.
Diagram 1:

1. The right ventricle pumps oxygen-poor blood to the two lungs via...
2. the pulmonary arteries
3. As the blood flows through capillaries in the lungs, it takes up oxygen and unloads carbon dioxide.
4. Oxygen-rich blood flows back through the pulmonary veins to...
5. left atrium
6. Next, the oxygen-rich blood flows from the left atrium into the left ventricle
7. The Left ventricle pumps blood to the systemic circuit. Oxygen-rich blood leaves the left ventricle through the aorta
   - The aorta is our largest blood vessel, with a diameter of roughly 2.5 cm, about the same diameter as a quarter. The first branches from the aorta are the coronary arteries, which supply blood to the heart muscle itself
8. Next are branches leading to the head, chest, and arms
9. Oxygen-poor blood from the upper body is channeled into a large vein called the superior vena cava, and the inferior vena cava, another large veins, returns blood form the lower body.
10. The two vena cavae empty into the right atrium

As the blood flows from the right atrium into the right ventricle, we complete our journey
Figure 6 – shows the path of blood through the heart. About the size of a clenched first, the human heart is enclosed in a sac just under the breastbone. The heart is formed mostly of cardiac muscle tissue. Its thin-walled atria collect blood returning to the heart. The thicker-walled ventricles pumps blood to the lungs and to all other body tissues. Notice that the left ventricle walls are thicker, a reflection of how much farther it pumps blood in the body. Flap-like valves between the atria and ventricles and at the openings to the pulmonary artery and the aorta regulate the direction of blood flow.
Diagram 2: When entire heart is relaxed, in the phase called diastole, blood flows into all four of its chambers. Blood enters the right atrium from the venae cavae and the left atrium from the pulmonary veins. The valves between the atria and the ventricles are open. Diastole lasts about 0.4 second, during which the ventricles nearly fill with blood. The contraction phase of the cardiac cycle is called systole. Systole begins with a very brief (0.1 second) contraction of the atria that completely fills the ventricles with blood. Then the ventricles contract for about 0.3 second. The force of their contraction closes the AV valves, opens the semilunar valves located at the exit from each ventricle, and pumps blood into the large arteries. Blood flows into the atria during the second part of systole, as the green arrows in step 3 indicate.

The volume of blood that each ventricle pumps per minute is called cardiac output. This volume is equal to the amount of blood pumped by a ventricle each time it contracts times the heart rate (number of beats per minute).
In certain kinds of heart disease, the heart’s self-pacing system fails to maintain a normal heart rhythm. The remedy is an artificial pacemaker, a tiny electronic device surgically implanted near the heart. Artificial pacemakers emit electrical signals that trigger normal heartbeats.
A heart attack, also called a myocardial infarction, is the damage or death of cardiac muscle tissue as a result of such blockage. Approximately one-third of heart attack victims die almost immediately. For those who survive, the ability of the damaged heart to pump blood may be seriously impaired.
The suddenness of a heart attack or stroke belies the fact that the arteries of most victims became impaired gradually by a chronic cardiovascular disease known as atherosclerosis. During the course of this disease, growths called plaques develop in the inner walls of arteries, narrowing the passages through which blood can flow. The artery wall becomes thickened and infiltrated with cholesterol and fibrous connective tissue. A blood clot formation.

**Figure 9**: Atherosclerosis: a normal artery (left) and an artery partially closed by plaque (right)
The blood vessels of the circulatory system must have an intimate connection with all the body's tissues. This face helps explain their remarkable total length.

Figure 9: the downwards arrows show the route that molecules take in diffusing from blood into tissue cells. Materials are not exchanged directly between blood and body cells. Each cell is immersed in interstitial fluid. Molecules such as \( \text{O}_2 \) and nutrients diffuse out of a capillary into the interstitial fluid and then from the interstitial fluid into a tissue cell. In addition, to transporting \( \text{O}_2 \) and nutrients, blood vessels convey metabolic wastes to waste disposal organs; \( \text{CO}_2 \) to lungs and a variety of other metabolic wastes to the kidneys. The upward arrows in the figure represents the diffusion of waste molecules out of a tissue cell, through the interstitial fluid and into the capillary.

Figure 10: Diffusion between blood and tissue cells
Structure of Blood Vessels

Figure 11 illustrates the structures of the different kinds of blood vessels and how the vessels are connected. Look first at the capillaries (center). Appropriate to its function of exchange of materials, a capillary has a very thin wall formed of a single layer of epithelial cells, which is wrapped in a thin basal lamina. The inner surface of the capillary is smooth and keeps the blood cells from being abraded as they tumble along.

Arteries, arterioles, veins, and venules have thicker walls than those of capillaries. Their walls have the same epithelial layer, but they are reinforced by two other tissue layers. An outer layer of connective tissue with elastic fibers enables the vessels to stretch and recoil. The middle layer consists mainly of smooth muscle. Both these layers are thicker and sturdier in arteries, providing the strength and elasticity to accommodate the rapid flow and higher pressure of blood pumped by the heart. Arteries are also able to regulate blood flow by constricting or relaxing their smooth muscle layer. The thinner-walled veins convey blood back to the heart at low velocity and pressure. Within large veins, flaps of tissue act as one-way valves, which permit blood to flow only toward the heart.
Blood pressure is the force that blood exerts against the walls of our blood vessels. Created by the pumping of the heart, blood pressure drives the flow of blood from the heart though arteries and arterioles to capillary beds. When the ventricles contact, blood is forced into the arteries faster than it can flow into the arterioles. This stretches the elastic walls of the arteries. You can feel this effect of blood pressure when you measure your heart rate by taking your pulse. The pulse is the rhythmic stretching of the arteries. You can see this sure in pressure as the pressure peaks in the top graph of figure

**Figure 12:** Blood pressure and velocity in the blood vessels
Diagram 3:

1. A typical blood pressure for healthy young adult is about 120/70
2. Once wrapped around the upper arm, where large arteries are accessible, the cuff is infolded until the pressure is strong enough to close the artery and cut off blood flow to the lower arm
3. A stethoscope is used to listen for sounds for blood flow below the cuff, and systolic blood pressure is the first measurement taken as the cuff is gradually deflated. The first sound of blood spurting through the constricted artery indicates that the blood pressure is stronger than the pressure exerted by the cuff. The pressure at this point is the systolic pressure
4. The sounds of blood flowing unevenly through the artery continues until the pressure of the cuff falls below the pressure of the artery during diastole. Blood now flows continuously through the artery, and the sound of blood ceases. The reading on the pressure gauge at this point is the diastolic pressure.
Figure 13: The control of capillary blood flow by precapillary sphincters

1. Blood flows through a capillary bed when its precapillary sphincters are relaxed
2. It bypasses the capillary bed when the sphincters are contracted
The diagram above shows part of capillary with blood flowing from its arterial end. One of the forces is blood pressure, which tends to push fluid outward. The other is osmotic pressure, a force that tends to draw fluid into the capillary because the blood has a higher concentration of solutes than the interstitial fluid. Proteins dissolved in the blood account for much of this high solute concentration.

The direction of fluid movement into or out of the capillary at any point depends on the difference between blood pressure and osmotic pressure. At the upstream (arterial) end of the capillary, the blood pressure exceeds the osmotic pressure, there is a net movement of fluid out of the capillary. At the downstream (venous) end of the capillary, the situation is reversed. As blood moves through the tiny capillaries, the blood pressure drops so much that the osmotic pressure outweighs it, and fluid reenters the capillary.
Blood consists of several types of cells suspended in a liquid called plasma. When a blood sample is taken, the cells can be separated from the plasma by spinning the sample in a centrifuge. The cellular elements, which make up about 45% of the volume of blood, settle to the bottom of the centrifuge tube, underneath the transparent, straw-colored plasma.

Plasma is about 90% water. Among its many solutes are inorganic salts in the form of dissolved ions. These ions have several functions, such as keeping the pH of the blood at about 7.4, regulating the ions in interstitial fluid needed for nerve and muscle function, and maintaining the osmotic balance between blood and interstitial.
Adequate numbers of red blood cells are essential for healthy body function. After circulating for three or four months, red blood cells are broken down and their molecules recycled. Much of the iron removed from the hemoglobin is returned to the bone marrow, where new red blood cells are formed at the amazing rate of 2 million per second.

An abnormally low amount of hemoglobin or a low number of red blood cells is a condition called anemia.
We don’t bleed to death because our blood contains self-sealing materials that are activated when blood vessels are injured. These sealants are platelets and the plasma protein fibrinogen.

The immediate response to an injury is constriction of the damaged blood vessel, reducing blood loss and allowing time for repairs to begin.

Diagram 5:
1. When the epithelium lining a blood vessel is damaged, connective tissue in the vessel is exposed to blood. Platelets rapidly adhere to the exposed tissue and release chemicals that make nearby platelets sticky.
2. Soon a cluster of sticky platelets forms a plug that provides fast protection against additional blood loss. Clotting factors released from the clumped platelets interact with clotting factors in the plasma, setting off a chain of reactions that culminates in the formation of a reinforced patch, called a scab when its on the skin. In this complex process, which involves more than a dozen different clotting factors, an enzyme is activated that converts fibrinogen to a threadlike protein called fibrin.
3. Threads of fibrin (white) trap blood cells and more platelets.
The red marrow of bones such as the ribs, vertebrae, breastbone, and pelvis all contain a spongy tissue in which unspecialized cells called multipotent stem cells differentiate into blood cells.

As shown in the figure above, multipotent stem cells give rise to two different types of stem cells: lymphoid stem cells give rise to lymphocytes, which function in the immune system, and myeloid stem cells produce erythrocytes, other white blood cells, and platelets. After forming in the early embryo, these stem cells continually produce all the blood cells needed throughout life.