19.6: Electricity in the World

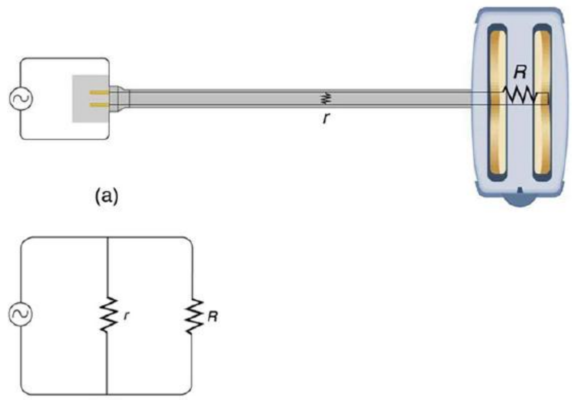
learning objectives

- Identify factors that determine the lethality of an electric shock

There are two known categories of electrical hazards: thermal hazards and shock hazards. A thermal hazard is when excessive electric power causes undesired thermal effects, such as starting a fire in the wall of a house. A shock hazard occurs when electric current passes through a person. Shocks range in severity from painful but otherwise harmless to heart-stoppingly lethal.

Thermal Hazards

Electric power causes undesired heating effects whenever electric energy is converted to thermal energy at a rate faster than it can be safely dissipated. A classic example of this is the short circuit, shown in. A short circuit is a low- resistance path between terminals of a voltage source. Insulation on the appliance's wires has worn through, allowing the two wires to come into contact. Such an undesired contact with a high voltage is called a short. Since the resistance of the short, r, is very small, the power dissipated in the short, $P = V^2/r$, is very large. For example, if V is 120 V and r is 0.100 Ω, then the power is 144 kW, much greater than that used by a typical household appliance. Thermal energy delivered at this rate will very quickly raise the temperature of surrounding materials, melting or perhaps igniting them.



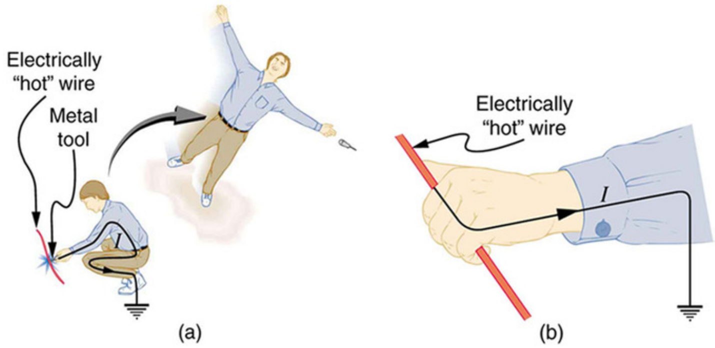
Short Circuit: A short circuit is an undesired low-resistance path across a voltage source. (a) Worn insulation on the wires of a toaster allows them to come into contact with a low resistance r. Since P = V2/r, thermal power is created so rapidly that the cord melts or burns. (b) A schematic of the short circuit.

A thermal hazard can be created even when a short circuit is not present if the wires in a circuit are overloaded with too much current. The power dissipated in the supply wires is $P = I^2R_w$, where R_w is the resistance of the wires and I the current flowing through them. If either I or R_w is too large, the wires overheat. Thermal hazards can cause moderate to severe burns to those who come in contact with the affected appliance or circuit.

Shock Hazards

Electric shock occurs upon contact of a body part with any source of electricity that causes a sufficient current through the skin, muscles, or hair. Typically, the expression is used to describe an injurious exposure to electricity.The minimum current a human can feel depends on the current type (AC or DC) and frequency. A person can feel at least 1 mA (rms) of AC current at 60 Hz and at least 5 mA of DC current. The current may, if it is high enough, cause tissue damage or fibrillation, which leads to cardiac arrest. 60 mA of AC (rms, 60 Hz) or 300-500 mA of DC can cause fibrillation.The potential severity of the shock depends on paths through the body that the currents take. If an electrical circuit is established by electrodes introduced in the body, bypassing the skin, then the potential for lethality is much higher if a circuit through the heart is established. This is known as a microshock. Currents of only 10 μA can be sufficient to cause fibrillation in this case.

A very dangerous possibility is the "can't let go" effect illustrated in. The muscles that close the fingers are stronger than those that open them, so the hand involuntarily closes around the wire shocking it. This can prolong the shock indefinitely. It can also be a danger to a person trying to rescue the victim, because the rescuer's hand may close about the victim's wrist. Usually the best way to help the victim is to give the fist a hard blow with an insulator or to throw an insulator at the fist.

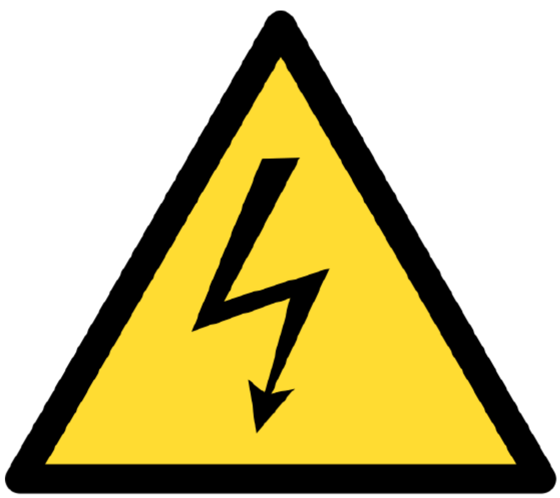


Electric Shock and Muscular Contractions: An electric current can cause muscular contractions with varying effects. (a) The victim is "thrown" backward by involuntary muscle contractions that extend the legs and torso. (b) The victim can't let go of the wire that is stimulating all the muscles in the hand. Those that close the fingers are stronger than those that open them.

Factors in the Lethality of Electric Shock

The lethality of an electric shock is dependent on several variables:

- Current: The higher the current, the more likely it is lethal. Since current is proportional to voltage when resistance is fixed (Ohm 's law), high voltage is an indirect risk for producing higher currents.
- Duration: The longer the duration, the more likely it is lethal — safety switches may limit the time of current flow.
- Pathway: If current flows through the heart muscle, it is more likely to be lethal.
- Very high voltage (over about 600 volts): This poses an additional risk beyond the simple ability of high voltage to cause high current at a fixed resistance. Very high voltage, enough to cause burns, will cause dielectric breakdown at the skin, actually lowering total body resistance and, ultimately, causing even higher current than when the voltage was first applied. Contact with voltages over 600 volts can cause enough skin burning to decrease the total resistance of a path though the body to 500 ohms or less.
- Frequency: Very high-frequency electric current causes tissue burning but does not penetrate the body far enough to cause cardiac arrest.



High Voltage Warning: International safety symbol "Caution, risk of electric shock" (ISO 3864), also known as the high-voltage symbol

Nerve Conduction and Electrocardiograms

Voltage pulses along a cell membrane, called action potentials, allow us to sense the world, control parts of our body, and think.

learning objectives

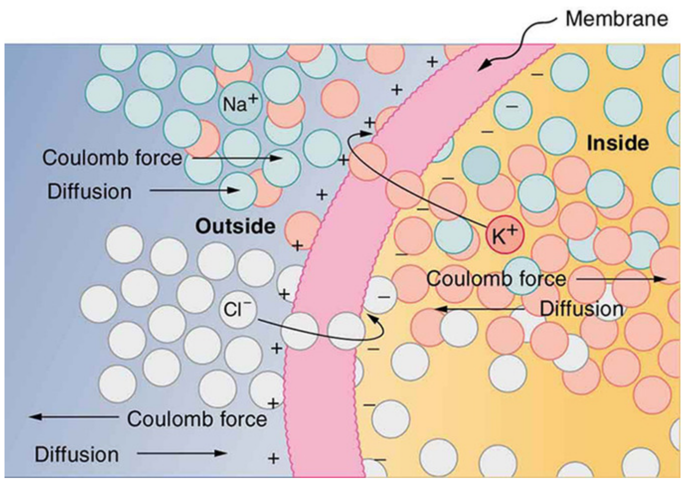
- Explain purpose of the electrocardiogram and identify functions performed by electric currents in the nerve system

Nerve Conduction and Electrocardiograms

Nerve Conduction

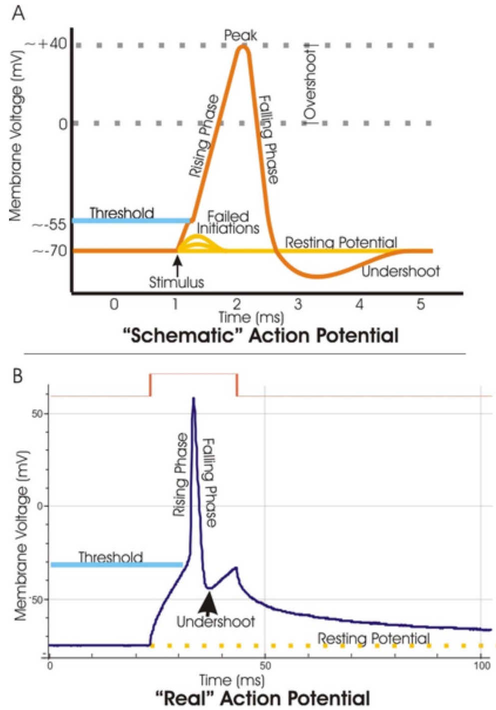
Electric currents in the complex system of nerves in our body allow us to sense the world, control parts of our body, and think. There are three major functions of nerves. First, nerves carry messages from our sensory organs to the central nervous system, consisting of the brain and spinal cord. Second, nerves carry messages from the central nervous system to muscles and other organs. Third, nerves transmit and process signals within the central nervous system.

Nerve conduction is a general term for electrical signals carried by nerve cells. A voltage is created across the cell membrane of a neuron in its resting state. This membrane separates electrically neutral fluids having differing concentrations of ions, the most important varieties being Na^+, K^+, and Cl^- (these are sodium, potassium, and chlorine ions). Free ions will diffuse from a region of high concentration to one of low concentration. The cell membrane is *semipermeable*, meaning that some ions may cross it while others cannot. In its resting state, the cell membrane is permeable to K^+ and Cl^-, and impermeable to Na^+. Diffusion of K^+ and Cl^- thus creates the layers of positive and negative charge on the outside and inside of the membrane, and the Coulomb force prevents the ions from diffusing across in their entirety.



Creating a Voltage Across a Cell Membrane: The semipermeable membrane of a cell has different concentrations of ions inside and out. Diffusion moves the K+ and Cl− ions in the direction shown, until the Coulomb force halts further transfer. This results in a layer of positive charge on the outside, a layer of negative charge on the inside, and thus a voltage across the cell membrane. The membrane is normally impermeable to Na+.

Once the charge layer has built up, the repulsion of like charges prevents more from moving across, and the attraction of unlike charges prevents more from leaving either side. The result is two layers of charge right on the membrane, with diffusion being balanced by the Coulomb force. A tiny fraction of the charges move across and the fluids remain neutral, while a separation of charge and a voltage have been created across the membrane. Electric currents along the cell membrane are created by any stimulus that changes the membrane's permeability. The membrane thus temporarily becomes permeable to Na^+, which then rushes in, driven both by diffusion and the Coulomb force. This inrush of Na+ first neutralizes the inside membrane (called depolarization), and then makes it slightly positive. The depolarization causes the membrane to again become impermeable to Na^+, and the movement of K^+ quickly returns the cell to its resting potential, referred to as repolarization. This sequence of events results in a voltage pulse, called the action potential and is shown in.



Voltage channels are critical in the generation of an action potential: Top: view of an idealized action potential shows its various phases as the action potential passes a point on a cell membrane. Bottom: Recordings of action potentials are often distorted compared to the schematic view because of variations in electrophysiological techniques used to make the recording.

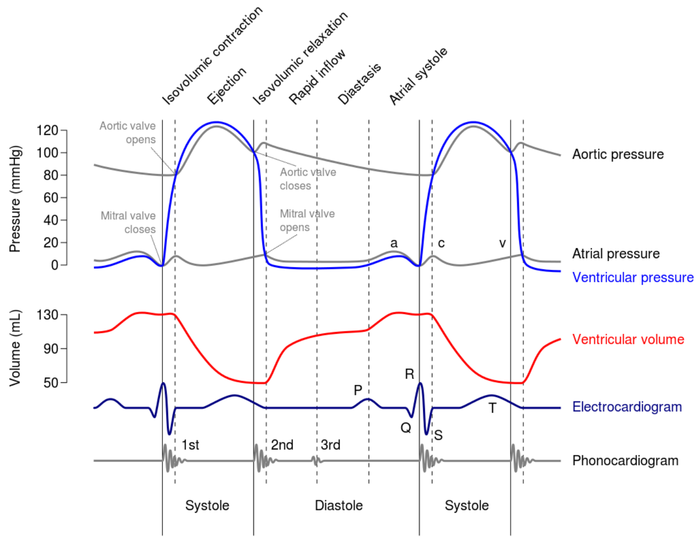
Only small fractions of the ions move, so that the cell can fire many hundreds of times without depleting the excess concentrations of Na+ and K+. This is an example of active transport, wherein cell energy is used to move ions across membranes against diffusion gradients and the Coulomb force. The action potential is a voltage pulse at one location on a cell membrane.

How does it get transmitted along the cell membrane as a nerve impulse ? The changing voltage and electric fields affect the permeability of the adjacent cell membrane, so that the same process takes place there. The adjacent membrane depolarizes, affecting the membrane farther down, and so on. Thus the action potential stimulated at one location triggers a nerve impulse that moves slowly (about 1 m/s) along the cell membrane.

Electrocardiograms

Just as nerve impulses are transmitted by depolarization and repolarization of an adjacent membrane, the depolarization that causes muscle contraction can also stimulate adjacent muscle cells to depolarize (fire) and contract. Thus, a depolarization wave can be sent across the heart, coordinating its rhythmic contractions and enabling it to perform its vital function of propelling blood through the circulatory system. An electrocardiogram (ECG) is a record of the voltages created by the wave of depolarization (and subsequent repolarization) in the heart. Historically, ECGs were performed by placing electrodes on the left and right arms and the left leg. The voltage between the right arm and the left leg is called the lead II potential and is an indicator of heart-muscle function.

shows an ECG of the lead II potential and a graph of other major events during the cardiac cycle. The major features are labeled P, Q, R, S, and T. The *P wave* is generated by the depolarization and contraction of the atria as they pump blood into the ventricles. The *QRS complex* has a characteristic shape and time span, and is created by the depolarization of the ventricles as they pump blood to the body. The lead II QRS signal also masks the repolarization of the atria. Finally, the *T wave*is generated by the repolarization of the ventricles and is followed by the P wave in the next heartbeat. Arterial blood pressure varies with each part of the heartbeat, with systolic (maximum) pressure occurring closely after the QRS complex, signaling the contraction of the ventricles.



ECG Curve: A normal ECG curve synchronized with other major events during the cardiac cycle.

Electric Activity in the Heart

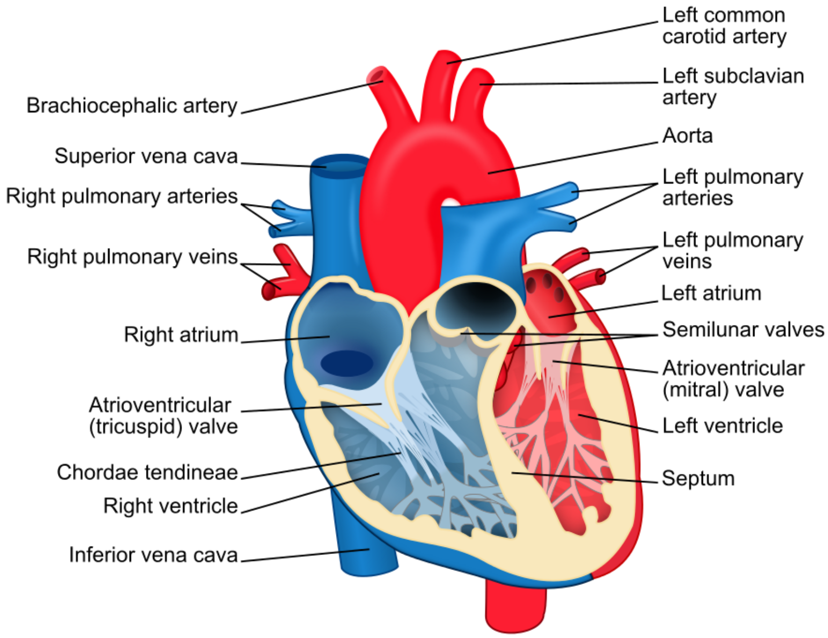
Electric energy stimulating the heart occurs in the sinoatrial node, the heart's pacemaker, and is transmitted partially by Perkinje fibers.

learning objectives

- Identify part of the heart that acts as a pacemaker

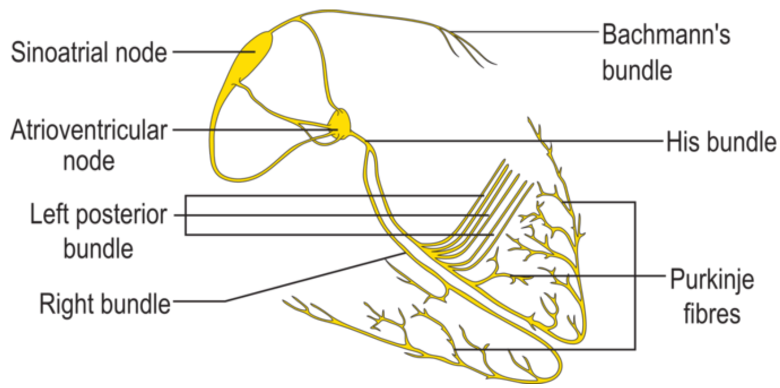
Electric Activity in the Heart

The human heart provides continuous blood circulation through the cardiac cycle and is unsurprisingly one of the most vital organs in the human body. The heart is divided into four main chambers: the two upper chambers are called the left and right atria (singular atrium) and two lower chambers are called the right and left ventricles. As can be seen in, there is a thick wall of muscle separating the right side and the left side of the heart called the septum. Normally with each beat the right ventricle pumps the same amount of blood into the lungs that the left ventricle pumps out into the body. Physicians commonly refer to the right atrium and right ventricle together as the right heart and to the left atrium and left ventricle as the left heart.



Structure of the heart: Structure diagram of a coronal section of the human heart from an anterior view. The two larger chambers are the ventricles.

The electric energy that stimulates the heart occurs in the sinoatrial node, which produces a definite potential and then discharges, sending an impulse across the atria. In the atria the electrical signal moves from cell to cell (see section on nerve conduction and the electrocardiogram) while in the ventricles the signal is carried by specialized tissue called the Purkinje fibers which then transmit the electric charge to the myocardium. shows the isolated heart conduction system.

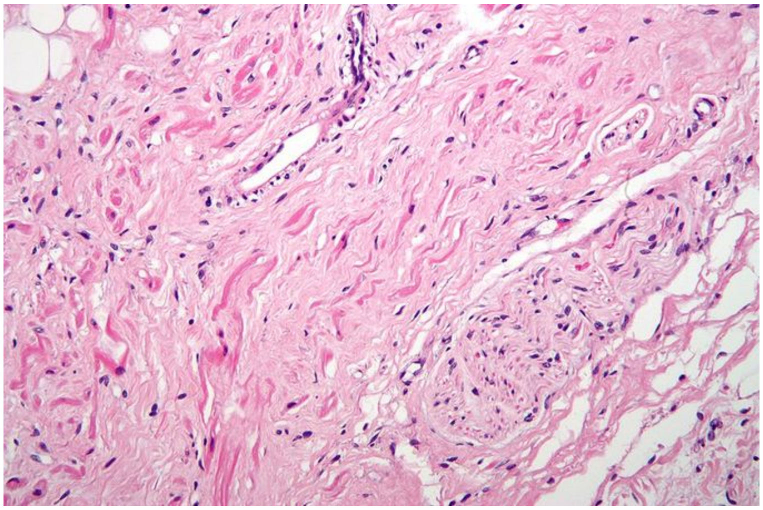


Conduction System of the Heart: Isolated heart conduction system, showing the sinoatrial and Purkinje fibers.

The Sinotrial Node's Role as a Pacemaker

The sinoatrial node (also commonly spelled sinuatrial node) is the impulse-generating (pacemaker) tissue located in the right atrium of the heart: i.e., generator of normal sinus rhythm. It is a group of cells positioned on the wall of the right atrium. These cells are specialized cardiomycetes (cardiac muscle cells).

The sinoatrial node (also commonly spelled sinuatrial node, abbreviated SA node) is the impulse-generating (pacemaker) tissue located in the right atrium of the heart, and thus the generator of normal sinus rhythm. It is a group of cells positioned on the wall of the right atrium. Although all of the heart's cells have the ability to generate the electrical impulses (or action potentials) that trigger cardiac contraction, the sinoatrial node normally initiates it, simply because it generates impulses slightly faster than the other areas with pacemaker potential.



Sinoatrial Node Tissue: High magnification micrograph of sinoatrial node tissue and an adjacent nerve fiber.

Cells in the SA node, located in the upper right corner of the heart, will typically discharge (create action potentials) at about 60-100 beats/minute. Because the sinoatrial node is responsible for the rest of the heart's electrical activity, it is sometimes called the primary pacemaker. If the SA node does not function, or the impulse generated in the SA node is blocked before it travels down the electrical conduction system, a group of cells further down the heart will become the heart's pacemaker. These cells form the atrioventricular node (AV node), which is an area between the atria and ventricles, within the atrial septum. If the AV node also fails, Purkinje fibers are capable of acting as the pacemaker. The reason Purkinje cells do not normally control the heart rate is that they generate action potentials at a lower frequency than the AV or SA nodes.

Purkinje Fibers

The Purkinje fibers are located in the inner ventricular walls of the heart. These fibers consist of specialized cardiomyocytes that are able to conduct cardiac action potentials more quickly and efficiently than any other cells in the heart. Purkinje fibers allow the heart's conduction system to create synchronized contractions of its ventricles, and are therefore essential for maintaining a consistent heart rhythm.

During the ventricular contraction portion of the cardiac cycle, the Purkinje fibers carry the contraction impulse from both the left and right bundle branch to the myocardium of the ventricles. This causes the muscle tissue of the ventricles to contract, thus enabling a force to eject blood out of the heart. Atrial and ventricular discharge through the Purkinje trees is assigned on a standard Electrocardiogram as the P Wave and QRS complex, respectively.

Purkinje fibers also have the ability of automatically firing at a rate of 15-40 beats per minute if left to their own devices. In contrast, the SA node outside of parasympathetic control can fire a rate of almost 100 beats per minute. In short, they generate action potentials, but at a slower rate than sinoatrial node and other atrial ectopic pacemakers. Thus they serve as the last resort when other pacemakers fail.

Key Points

- Electric power causes undesired heating effects whenever electric energy is converted to thermal energy at a rate faster than it can be safely dissipated, such as in the case of a short circuit. This is referred to as a thermal hazard.
- A shock hazard occurs when electric current passes through a person. If the current is high enough it can cause tissue damage or fibrillation, which can lead to cardiac arrest.
- The lethality of an electric shock is dependent on many variables, including current, duration, pathway, and the presence or absence of very high voltage.
- Nerves carry messages from our sensory organs to the central nervous system, from the central nervous system to muscles, and within the central nervous system itself.
- The effects of diffusion and the Coulomb force act together to allow ions like Na+, K+, and Cl- to create a voltage across cell membranes.
- An action potential is an event which alters the permeability of a cell membrane due to electric currents.

- The depolarization that causes muscle contraction can also stimulate contraction in adjacent muscle cells. A depolarization wave across the heart is responsible for rhythmic contractions. An electrocardiogram (ECG) is a record of the voltages in the heart.
- The human heart provides continuous blood circulation through the cardiac cycle and is unsurprisingly one of the most vital organs in the human body.
- The heart is divided into four main chambers: the two upper chambers are called the left and right atria (singular atrium) and two lower chambers are called the right and left ventricles. See for an illustration. There is a conduction system that transports impulses through the heart.
- The electric energy that stimulates the heart occurs in the sinoatrial node, which produces a definite potential and then discharges, sending an impulse across the atria. It is thus the generator of normal sinus rhythm and functions as the heart's pacemaker.
- In the atria the electrical signal moves from cell to cell while in the ventricles the signal is carried by specialized tissue called the Purkinje fibers.
- Purkinje fibers allow the heart's conduction system to create synchronized contractions of its ventricles, and are therefore essential for maintaining a consistent heart rhythm.

Key Terms

- **shock hazard**: an electrical hazard that poses the risk of passing current through the body
- **thermal hazard**: an electrical hazard caused by overheating (e.g., in a resistive element)
- **fibrillation**: the rapid, irregular, and unsynchronized contraction of the muscle fibers of the heart
- **diffusion**: the intermingling of the molecules of a fluid due to random thermal agitation
- **electrocardiogram**: The visual output that an electrocardiograph produces
- **action potential**: A short term change in the electrical potential that travels along a cell such as a nerve or muscle fiber.
- **sinoatrial node**: a group of specialized cardiac muscle cells (tissue) located in the right atrium of the heart, which generates the impulses that establish the normal sinus rhythm.
- **Purkinje fibers**: specialized cardiac muscle cells that are able to conduct cardiac muscle potentials quickly and efficiently; essential for maintaining consistent heart rhythm.
- **myocardium**: The middle of the three layers forming the wall of the heart.

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