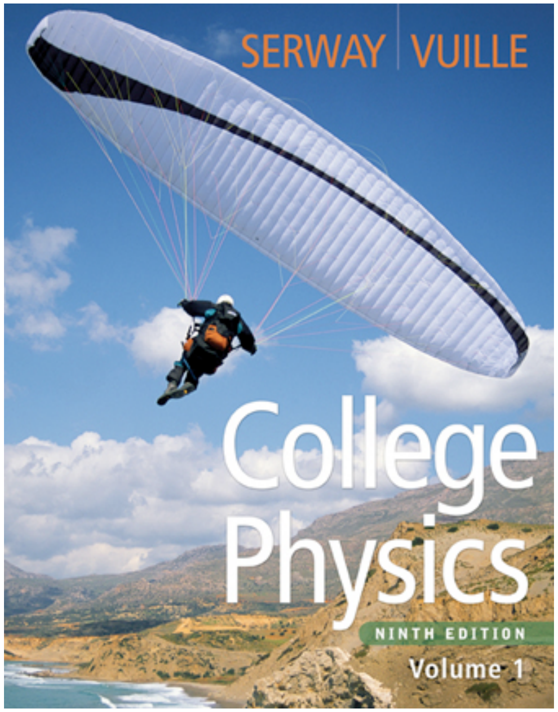

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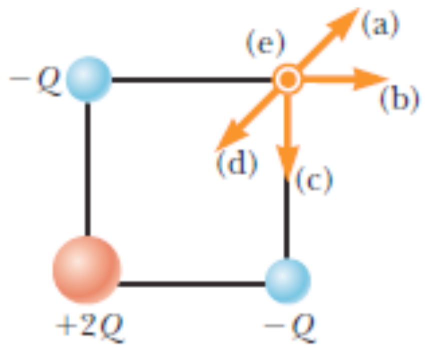
Chapter 17

Current and Resistance

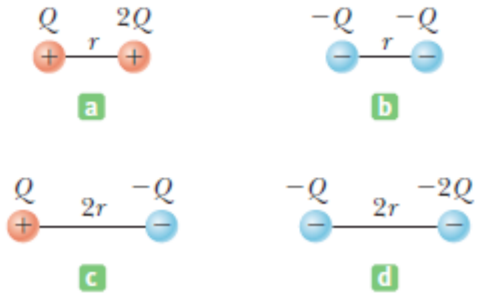
1. Three charged particles are arranged on corners of a square as shown in Figure MCQ15.12, with charge -Q on both the particle at the upper left corner and the particle at the lower right corner, and charge +2Q on the particle at the lower left right corner. What is the direction of the electric field at the upper right corner which is a point in empty space? (a) upward and to the right (b) to the right (c) downward (d) downward and to the left (e) The field is exactly zero at that point.



2. If more electric field lines leave a Gaussian surface than enter it, what can you conclude about the net charge enclosed by that surface?

3. Why is it important to avoid sharp edges or points on conductors used in high-voltage equipment?

4. Rank the potential energies of the four systems of particles shown in Figure from largest to smallest.
Include equalities if appropriate.

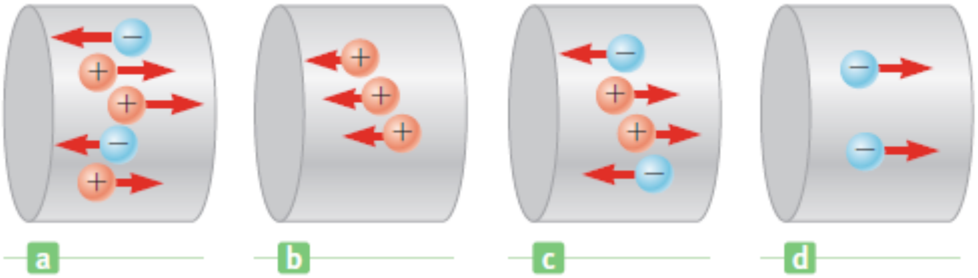


Quiz 3

(Must show work to get full credit)

1. If three unequal capacitors, initially uncharged, are connected in series across a battery, which of the following statements is true? (a) The equivalent capacitance is greater than any of the individual capacitances.(b) The largest voltage appears across the capacitor with the smallest capacitance. (c) The largest voltage appears across the capacitor with the largest capacitance. (d) The capacitor with the largest capacitance has the greatest charge. (e) The capacitor with the smallest capacitance has the smallest charge.

2. Consider positive and negative charges moving horizontally through the four regions in Figure. Rank the magnitudes of the currents in these four regions from lowest to highest.



Current

- Practical applications were based on static electricity.
- A steady source of electric current allowed scientists to learn how to control the flow of electric charges in circuits.

Electric Current

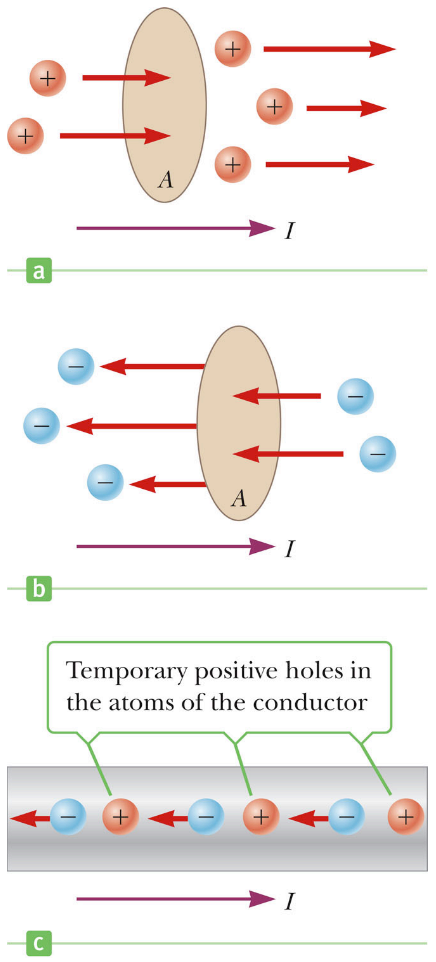
- The current is the **rate at which the charge flows through a surface.**
  - Look at the charges flowing perpendicularly through a surface of area A.
  - $$I_{av} \equiv \frac{\Delta Q}{\Delta t}$$
- The SI unit of current is Ampere (A)
  - 1 A = 1 C/s

Instantaneous Current

- The instantaneous current is the limit of the average current as the time interval goes to zero:
-
$$I = \lim_{\Delta t \to 0} I_{av} = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t}$$
-
- If there is a steady current, the average and instantaneous currents will be the same.
- SI unit: A
-

Electric Current, Cont.

- The direction of the current is the direction positive charge would flow.
  - This is known as *conventional current direction.*
- In a common conductor, such as copper, the current is due to the motion of the negatively charged electrons.
- It is common to refer to a moving charge as a mobile *charge carrier.*
  - A charge carrier can be positive or negative.

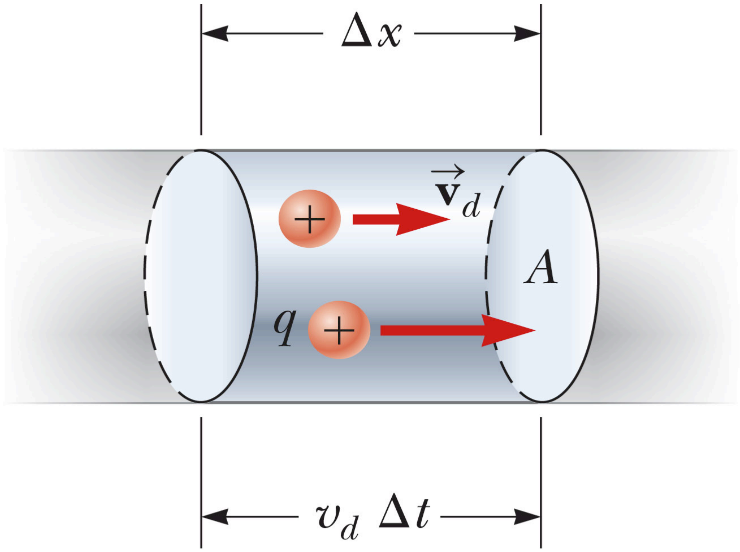


Power

- In a conductor carrying a current, the electric potential of the charges is continually decreasing.
- Positive charges move from regions of high potential to regions of low potential.
- $\Delta U_{charges} = q \Delta V$ is negative
  - Often only the magnitude is desired
- The power delivered to the circuit element is the energy divided by the elapsed time.

Current and Drift Speed

- Charged particles move through a conductor of cross-sectional area A.
- n is the number of charge carriers per unit volume.
- n A Δx is the total number of charge carriers.



Current and Drift Speed, Cont.

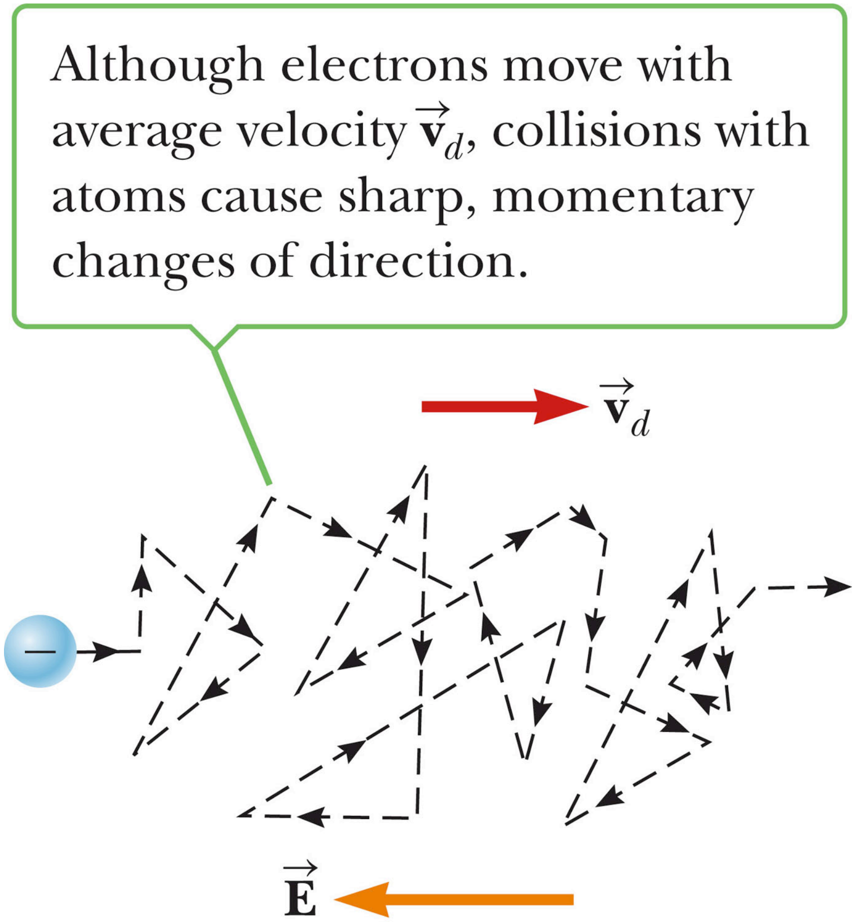
- The total charge is the number of carriers times the charge per carrier, q
  - $\Delta Q = (n\,A\,\Delta x)\,q$
- The drift speed, v_d, is the speed at which the carriers move.
  - $v_d = \Delta x / \Delta t$
- Rewritten: $\Delta Q = (n\,A\,v_d\,\Delta t)\,q$
- Finally, current, $I = \Delta Q/\Delta t = nqv_dA$
-

Current and Drift Speed, Final

- If the conductor is isolated, the electrons undergo random motion.
- When an electric field is set up in the conductor, it creates an electric force on the electrons and hence a current.

Charge Carrier Motion in a Conductor

- The zig-zag black line represents the motion of a charge carrier in a conductor.
  - The net drift speed is small.
- The sharp changes in direction are due to collisions.
- The net motion of electrons is opposite the direction of the electric field.



Although electrons move with average velocity $\vec{\mathbf{v}}_d$, collisions with atoms cause sharp, momentary changes of direction.

Electrons in a Circuit

- Assume you close a switch to turn on a light.
- The electrons do not travel from the switch to the bulb.
- The electrons already in the bulb move in response to the electric field set up in the completed circuit.
- A battery in a circuit supplies energy (not charges) to the circuit.

The amount of charge that passes through the filament of a certain lightbulb in 2.00 s is 1.67 C. Find (𝔞) the average current in the lightbulb and (𝔟) the number of electrons that pass through the filament in 5.00 s. (𝔠) If the current is supplied by a 12.0-V battery, what total energy is delivered to the lightbulb filament? What is the average power?

$$I_{\text{av}} = \frac{\Delta Q}{\Delta t} = \frac{1.67\ \text{C}}{2.00\ \text{s}} = \boxed{0.835\ \text{A}}$$

(1) $Nq = I_{\text{av}}\,\Delta t$

$$N(1.60 \times 10^{-19}\ \text{C/electron}) = (0.835\ \text{A})(5.00\ \text{s})$$

$$N = \boxed{2.61 \times 10^{19}\ \text{electrons}}$$

(2) $\Delta U = q\Delta V = (1.67\ \text{C})(12.0\ \text{V}) = \boxed{20.0\ \text{J}}$

$$P_{\text{av}} = \frac{\Delta U}{\Delta t} = \frac{20.0\ \text{J}}{2.00\ \text{s}} = \boxed{10.0\ \text{W}}$$

Electrons in a Circuit, Cont.

- The drift speed is much smaller than the average speed between collisions.
- When a circuit is completed, the electric field travels with a speed close to the speed of light.
- Although the drift speed is on the order of 10^{-4} m/s, the effect of the electric field is felt on the order of 10^{8} m/s.

A copper wire of cross-sectional area 3.00×10^{-26} m^2 carries a current of 10.0 A. (a) Assuming each copper atom contributes one free electron to the metal, find the drift speed of the electrons in this wire. (b) Use the ideal gas model to compare the drift speed with the random rms speed an electron would have at 20.0°C. The density of copper is

$8.92\ g/cm^3$, and its atomic mass is 63.5 u.

$$V = \frac{m}{\rho} = \frac{63.5\text{ g}}{8.92\text{ g/cm}^3} = 7.12\text{ cm}^3$$

$$7.12\text{ cm}^3\left(\frac{1\text{ m}}{10^2\text{ cm}}\right)^3 = 7.12 \times 10^{-6}\text{ m}^3$$

$$n = \frac{6.02 \times 10^{23}\text{ electrons/mole}}{7.12 \times 10^{-6}\text{ m}^3\text{/mole}}$$

$$= 8.46 \times 10^{28}\text{ electrons/m}^3$$

$$v_d = \frac{I}{nqA}$$

$$= \frac{10.0\text{ C/s}}{(8.46 \times 10^{28}\text{ electrons/m}^3)(1.60 \times 10^{-19}\text{ C})(3.00 \times 10^{-6}\text{ m}^2)}$$

$$v_d = \boxed{2.46 \times 10^{-4}\text{ m/s}}$$

$$v_{\text{rms}} = \sqrt{\frac{3k_BT}{m_e}}$$

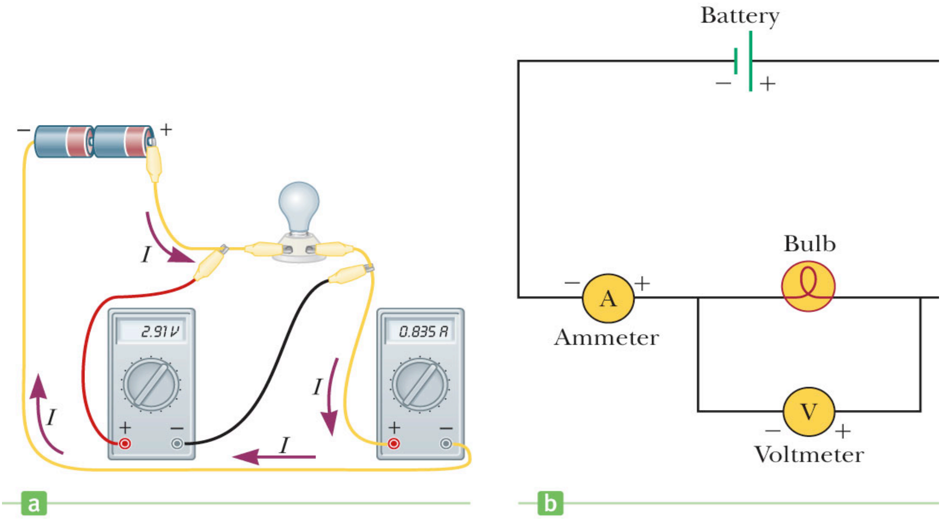
$$v_{\text{rms}} = \sqrt{\frac{3(1.38 \times 10^{-23}\,\text{J/K})(293\,\text{K})}{9.11 \times 10^{-31}\,\text{kg}}}$$

$$= \boxed{1.15 \times 10^{5}\,\text{m/s}}$$

Circuits

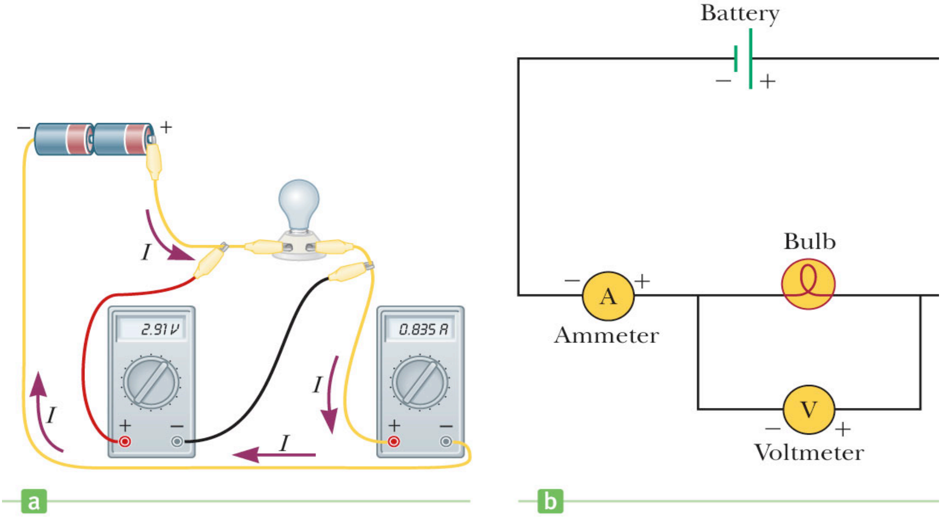
- A circuit is a closed path of some sort around which current circulates.
- A circuit diagram can be used to represent the circuit.
- Quantities of interest are generally current and potential difference.

Meters in a Circuit – Ammeter



- An ammeter is used to measure current.
  - –In line with the bulb, all the charge passing through the bulb also must pass through the meter.

Meters in a Circuit – Voltmeter



- A voltmeter is used to measure voltage (potential difference).
  - Connects to the two contacts of the bulb

Resistance

- In a conductor, the voltage applied across the ends of the conductor is proportional to the current through the conductor.
- The constant of proportionality is the *resistance* of the conductor.

$$R \equiv \frac{\Delta V}{I}$$

Resistance, Cont.

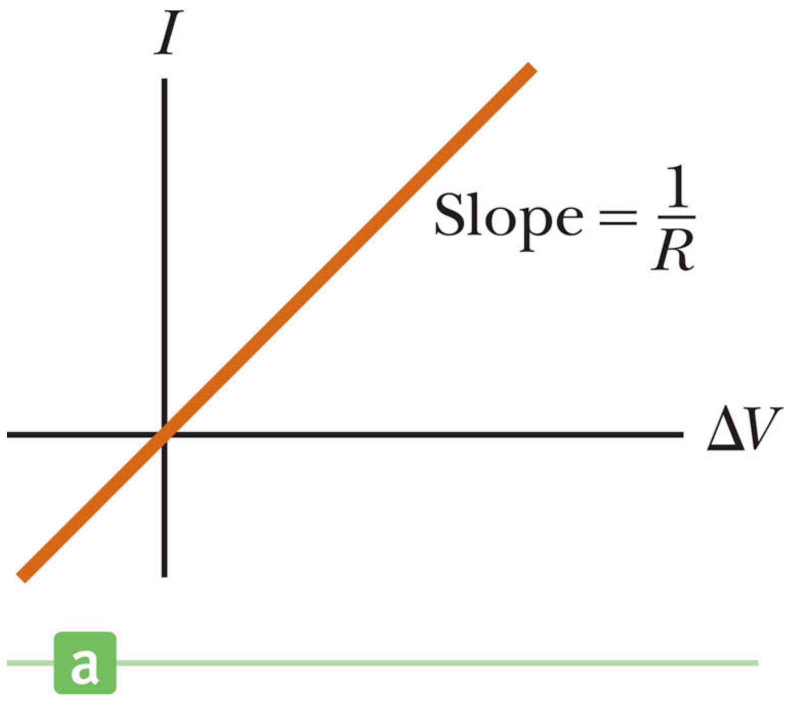
- Units of resistance are *ohms* (Ω)
  - 1 Ω = 1 V / A
- Resistance in a circuit arises due to collisions between the electrons carrying the current with the fixed atoms inside the conductor.

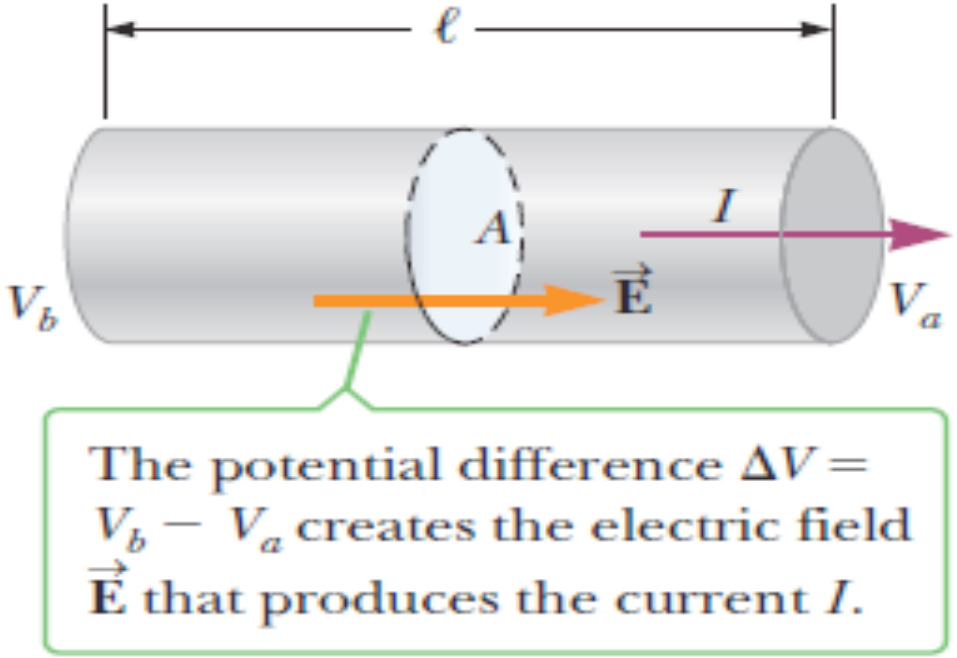
Ohm’s Law

- Experiments show that for many materials, including most metals, the resistance remains constant over a wide range of applied voltages or currents.
- This statement has become known as *Ohm’s Law.*
  - $\Delta V = I R$
- Ohm’s Law is an empirical relationship that is valid only for certain materials.
  - Materials that obey Ohm’s Law are said to be *ohmic.*

Ohm’s Law, Cont.

- An ohmic device
- The resistance is constant over a wide range of voltages.
- The relationship between current and voltage is linear.
- The slope is related to the resistance.



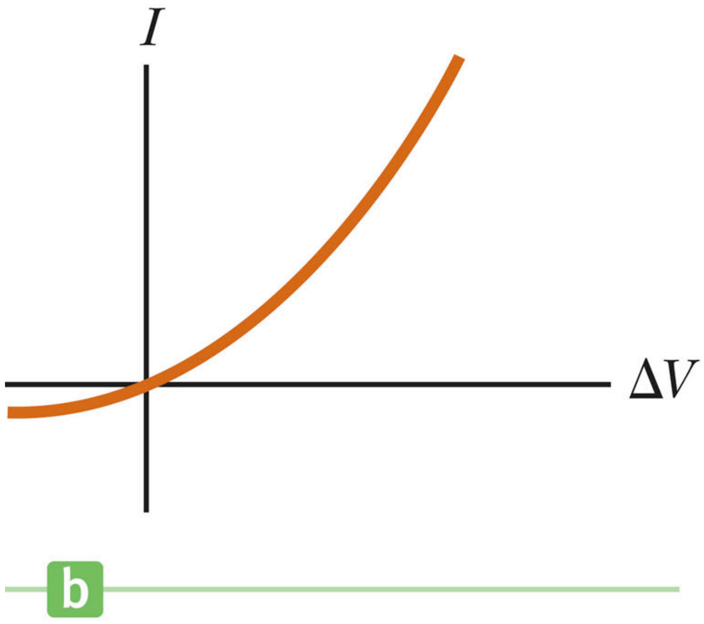


The potential difference $\Delta V = V_b - V_a$ creates the electric field $\vec{\mathbf{E}}$ that produces the current I.

Figure 17.7 A uniform conductor of length ℓ and cross-sectional area A. The current I is proportional to the potential difference or, equivalently, to the electric field and length.

Ohm’s Law, Final

- Non-ohmic materials are those whose resistance changes with voltage or current.
- The current-voltage relationship is nonlinear.
- A diode is a common example of a non-ohmic device.



Resistivity

- The resistance of an ohmic conductor is proportional to its length, L, and inversely proportional to its cross-sectional area, A.

$$R = \rho \frac{\ell}{A}$$

  - ρ is the constant of proportionality and is called the *resistivity* of the material.
  - See table 17.1

Table 17.1 Resistivities and Temperature Coefficients of Resistivity for Various Materials (at 20°C)

Material	Resistivity ($\Omega \cdot m$)	Temperature Coefficient of Resistivity [$(°C)^{-1}$]
Silver	1.59×10^{-8}	3.8×10^{-3}
Copper	1.7×10^{-8}	3.9×10^{-3}
Gold	2.44×10^{-8}	3.4×10^{-3}
Aluminum	2.82×10^{-8}	3.9×10^{-3}
Tungsten	5.6×10^{-8}	4.5×10^{-3}
Iron	10.0×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[a]	150×10^{-8}	0.4×10^{-3}
Carbon	3.5×10^{-5}	-0.5×10^{-3}
Germanium	0.46	-48×10^{-3}
Silicon	640	-75×10^{-3}
Glass	10^{10}–10^{14}	
Hard rubber	$\approx 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

[a] A nickel-chromium alloy commonly used in heating elements.

Temperature Variation of Resistivity

- For most metals, resistivity increases with increasing temperature.
  - With a higher temperature, the metal’s constituent atoms vibrate with increasing amplitude.
  - The electrons find it more difficult to pass through the atoms.

Temperature Variation of Resistivity, Cont.

- For most metals, resistivity increases approximately linearly with temperature over a limited temperature range.
- $$\rho = \rho_o[1+\alpha(T-T_o)]$$
  - ρ is the resistivity at some temperature T
  - ρ_o is the resistivity at some reference temperature T_o
- T_o is usually taken to be 20° C
  - is the **temperature coefficient of resistivity**
  -

Temperature Variation of Resistance

- Since the resistance of a conductor with uniform cross sectional area is proportional to the resistivity, you can find the effect of temperature on resistance.
- $$R = R_o[1+\alpha(T - T_o)]$$

Electrical Energy in a Circuit

- In a circuit, as a charge moves through the battery, the electrical potential energy of the system is increased by $\Delta Q \Delta V$.
  - The chemical potential energy of the battery decreases by the same amount.
- As the charge moves through a resistor, it loses this potential energy during collisions with atoms in the resistor.
  - The temperature of the resistor will increase.

(𝔞) Calculate the resistance per unit length of a 22-gauge Nichrome wire of radius 0.321 mm. (𝔟) If a potential difference of 10.0 V is maintained across a 1.00-m length of the Nichrome wire, what is the current in the wire? (𝔠) The wire is melted down and recast with twice its original length. Find the new resistance RN as a multiple of the old resistance RO.

$$A = \pi r^2 = \pi(0.321 \times 10^{-3}\,\mathrm{m})^2 = 3.24 \times 10^{-7}\,\mathrm{m}^2$$

$$\frac{R}{\ell} = \frac{\rho}{A} = \frac{1.5 \times 10^{-6}\,\Omega \cdot \mathrm{m}}{3.24 \times 10^{-7}\,\mathrm{m}^2} = \boxed{4.6\,\Omega/\mathrm{m}}$$

$$I = \frac{\Delta V}{R} = \frac{10.0\,\mathrm{V}}{4.6\,\Omega} = \boxed{2.2\,\mathrm{A}}$$

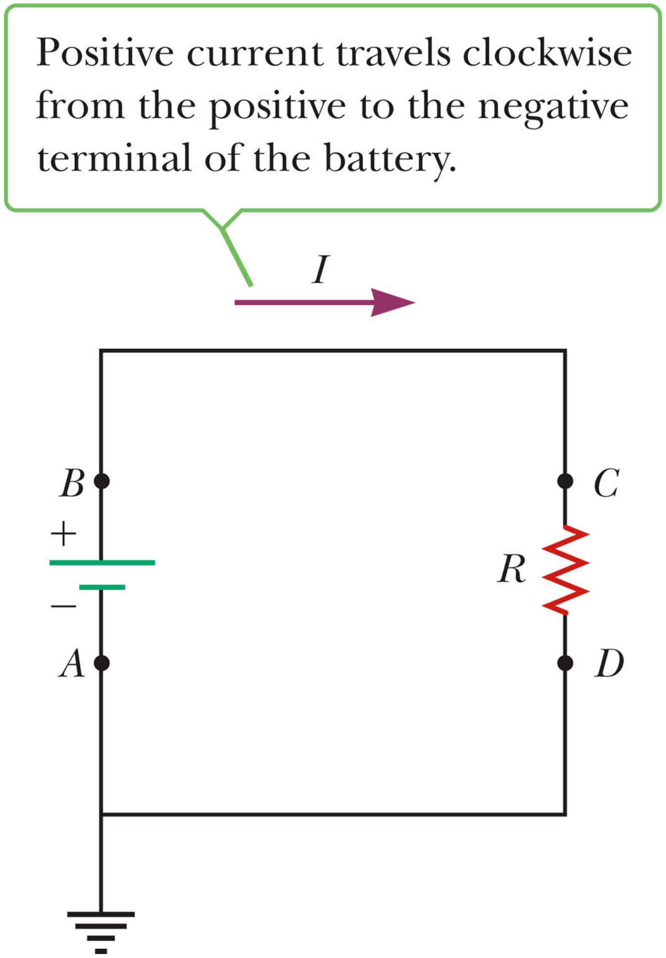
$$V_N = V_O \rightarrow A_N\ell_N = A_O\ell_O \rightarrow A_N = A_O(\ell_O/\ell_N)$$

$$A_N = A_O(\ell_O/2\ell_O) = A_O/2$$

$$R_N = \frac{\rho\ell_N}{A_N} = \frac{\rho(2\ell_O)}{(A_O/2)} = 4\,\frac{\rho\ell_O}{A_O} = \boxed{4R_O}$$

Energy Transfer in the Circuit

- Consider the circuit shown.
- Imagine a quantity of positive charge, ΔQ, moving around the circuit from point A back to point A.



Positive current travels clockwise from the positive to the negative terminal of the battery.

Energy Transfer in the Circuit, Cont.

- Point A is the reference point.
  - It is grounded and its potential is taken to be zero.
- As the charge moves through the battery from A to B, the potential energy of the system increases by QV.
  - The chemical energy of the battery decreases by the same amount.

Energy Transfer in the Circuit, Final

- As the charge moves through the resistor, from C to D, it loses energy in collisions with the atoms of the resistor.
- The energy is transferred to internal energy.
- When the charge returns to A, the net result is that some chemical energy of the battery has been delivered to the resistor and caused its temperature to rise.

Electrical Energy and Power, Cont.

- The rate at which the energy is lost is the power.

$$P = \frac{\Delta Q}{\Delta t}\Delta V = I\Delta V$$

- From Ohm's Law, alternate forms of power are

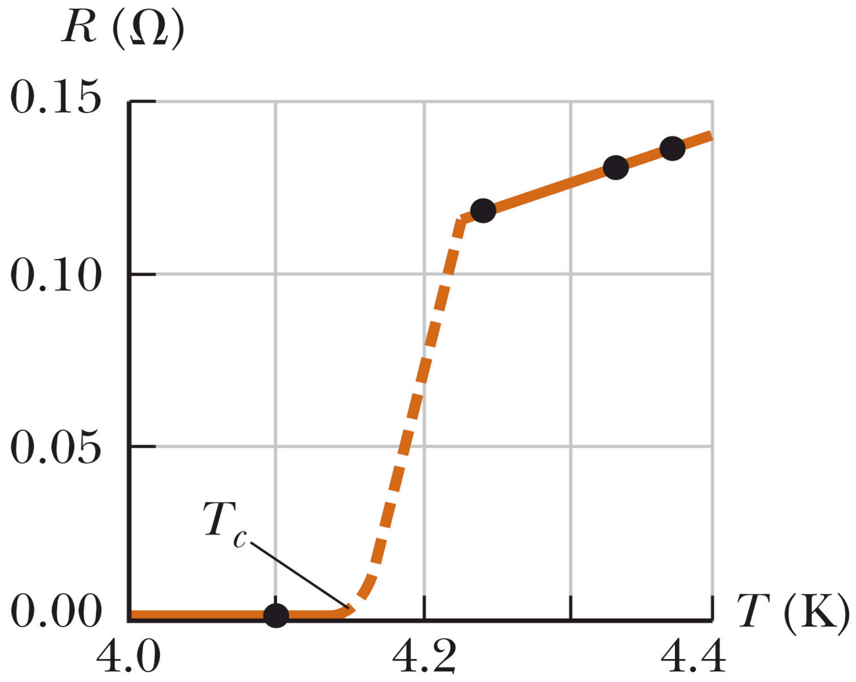
$$P = I^2 R = \frac{\Delta V^2}{R}$$

Electrical Energy and Power, Final

- The SI unit of power is Watt (W).
  - I must be in Amperes, R in ohms and □V in Volts
- The unit of energy used by electric companies is the *kilowatt-hour.*
  - This is defined in terms of the unit of power and the amount of time it is supplied.
  - 1 kWh = 3.60×10^6 J

Superconductors

- A class of materials and compounds whose resistances fall to virtually zero below a certain temperature, T_C
  - T_C is called the critical temperature
- The graph is the same as a normal metal above T_C, but suddenly drops to zero at T_C



Superconductors, Cont.

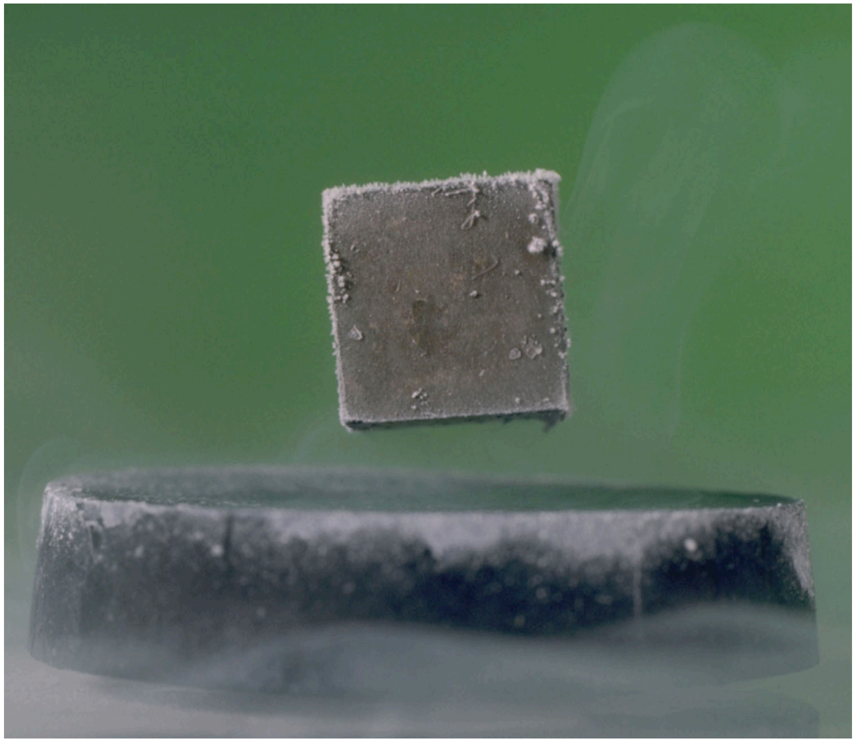
- The value of T_C is sensitive to
  - Chemical composition
  - Pressure
  - Crystalline structure
- Once a current is set up in a superconductor, it persists without any applied voltage.
  - Since $R = 0$

Superconductor Timeline

- 1911
  - Superconductivity discovered by H. Kamerlingh Onnes
- 1986
  - High temperature superconductivity discovered by Bednorz and Müller
  - Superconductivity near 30 K
- 1987
  - Superconductivity at 96 K and 105 K
- Current
  - Superconductivity at 150 K
  - More materials and more applications

Superconductor, Final

- Good conductors do not necessarily exhibit superconductivity.
- One application is the construction of superconducting magnets.
-

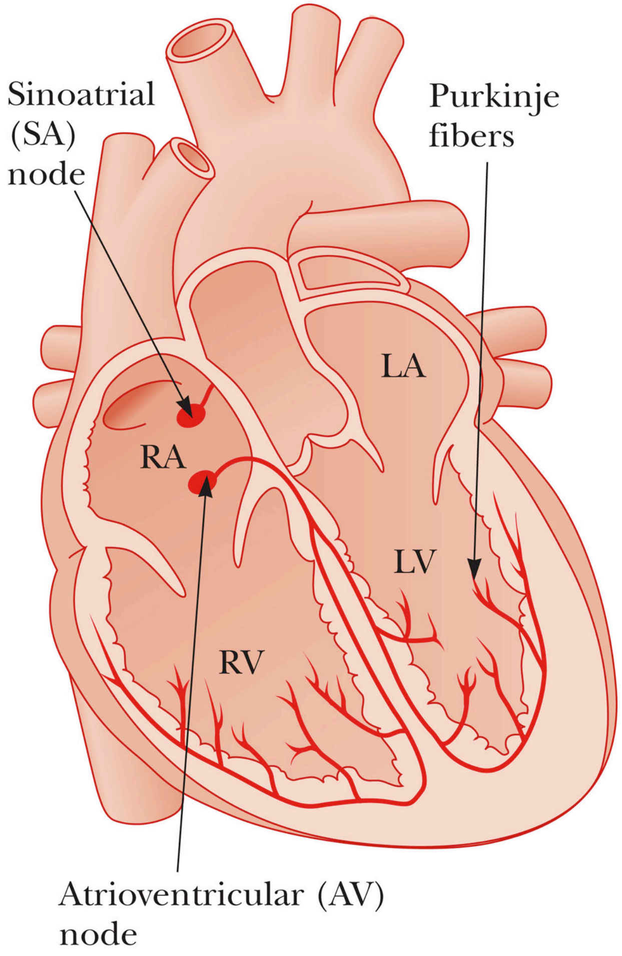


Electrical Activity in the Heart

- Every action involving the body’s muscles is initiated by electrical activity.
- Voltage pulses cause the heart to beat.
- These voltage pulses are large enough to be detected by equipment attached to the skin.

Operation of the Heart

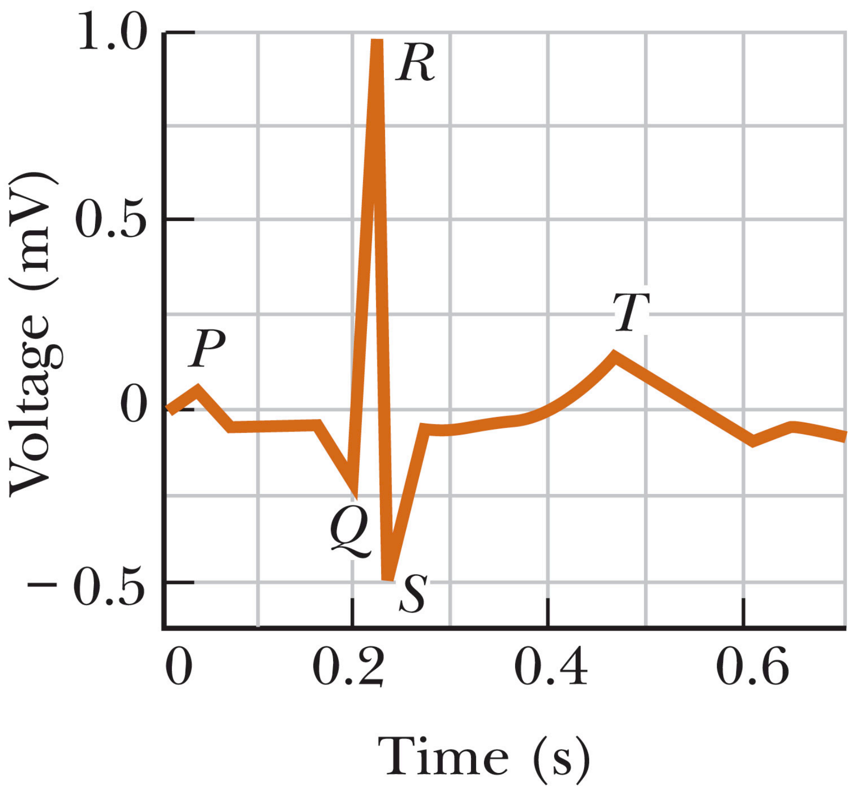
- The sinoatrial (SA) node initiates the heartbeat.
- The electrical impulses cause the right and left artial muscles to contract.
- When the impulse reaches the atrioventricular (AV) node, the muscles of the atria begin to relax.
- The ventricles relax and the cycle repeats.



Section 17.8

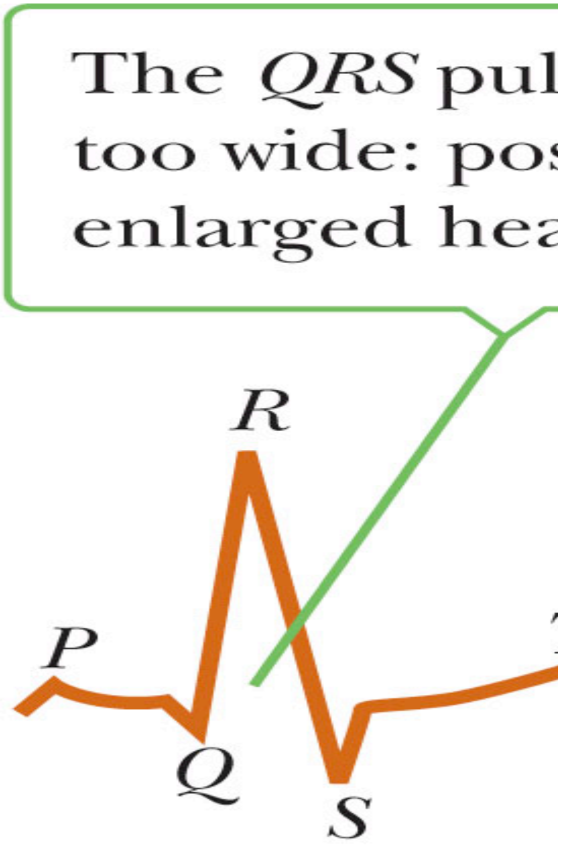
Electrocardiogram (EKG)

- A normal EKG
- P occurs just before the atria begin to contract.
- The QRS pulse occurs in the ventricles just before they contract.
- The T pulse occurs when the cells in the ventricles begin to recover.

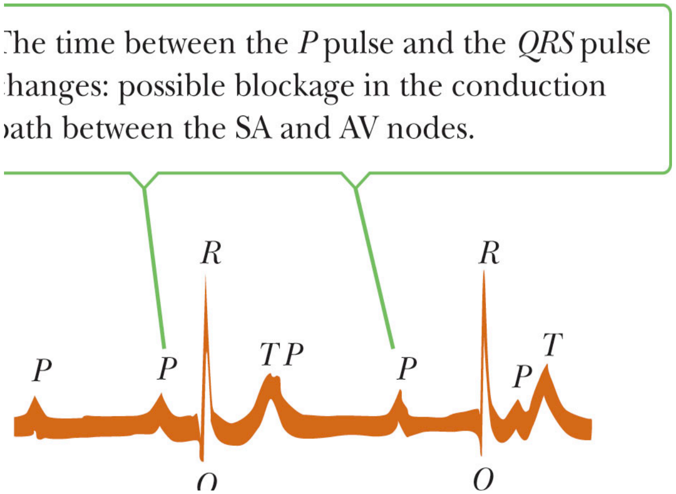


Abnormal EKG, 1

- The QRS portion is wider than normal.
- This indicates the possibility of an enlarged heart.

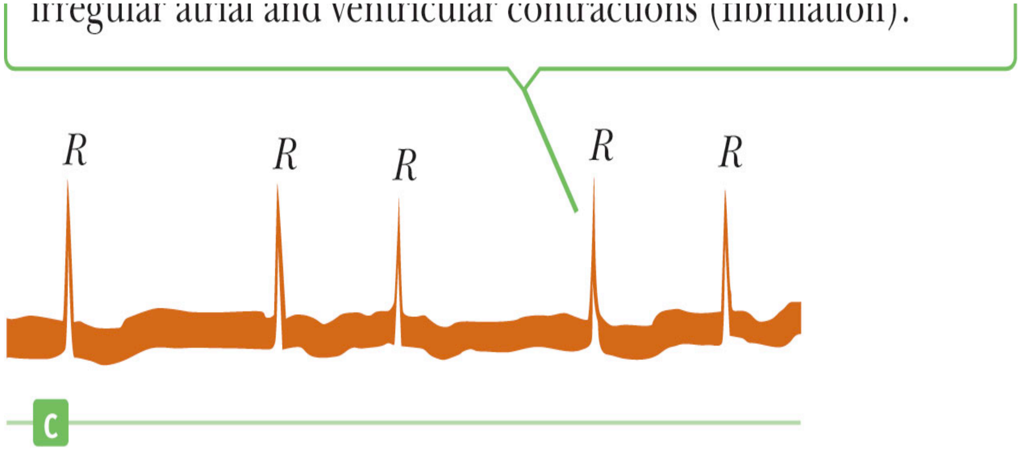


Abnormal EKG, 2



- There is no constant relationship between P and QRS pulse.
- This suggests a blockage in the electrical conduction path between the SA and the AV nodes.
- This leads to inefficient heart pumping.

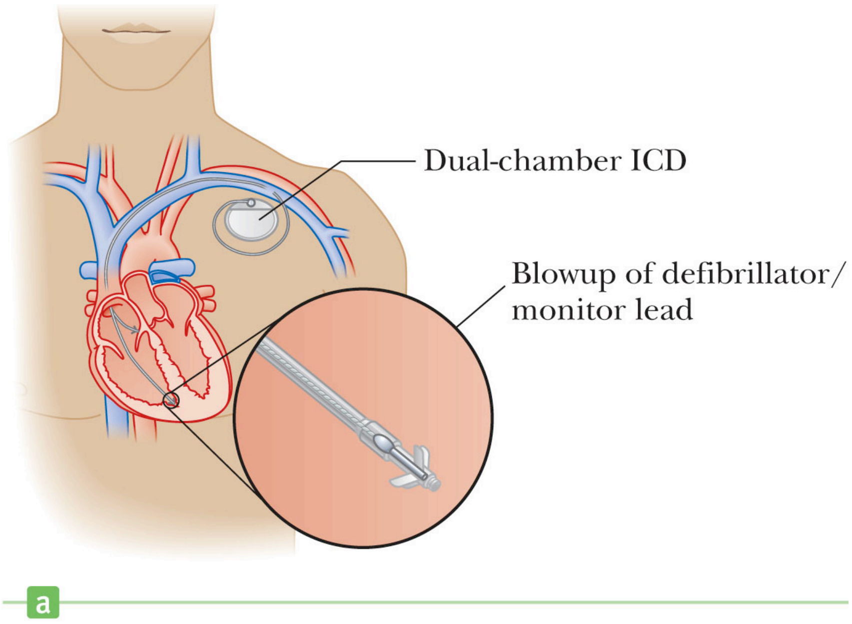
Abnormal EKG, 3



- No P pulse and an irregular spacing between the QRS pulses
- Symptomatic of irregular atrial contraction, called *fibrillation*
- The atrial and ventricular contraction are irregular.

Implanted Cardioverter Defibrillator (ICD)

- Devices that can monitor, record and logically process heart signals
- Then supply different corrective signals to hearts that are not beating correctly



Functions of an ICD

- Monitor atrial and ventricular chambers
  - Differentiate between arrhythmias
- Store heart signals for read out by a physician
- Easily reprogrammed by an external magnet

More Functions of an ICD

- Perform signal analysis and comparison
- Supply repetitive pacing signals to speed up or slow down a malfunctioning heart
- Adjust the number of pacing pulses per minute to match patient's activity