Lecture 3

Chapter 17 Current

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

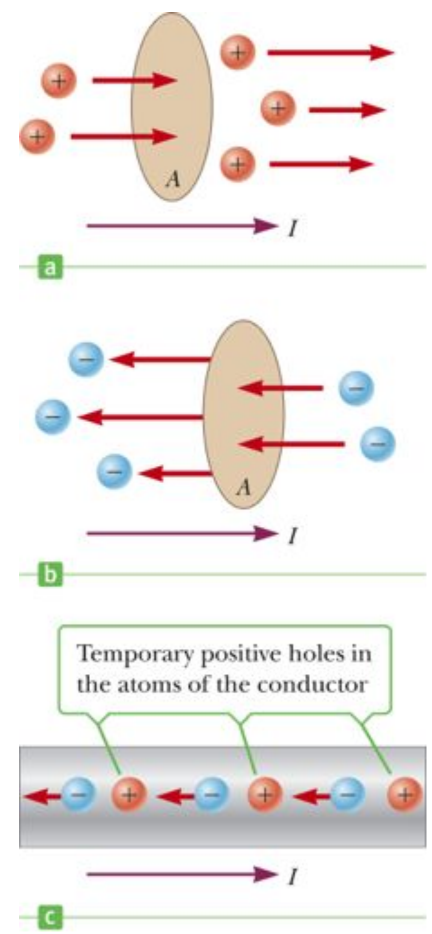
- The instantaneous current is the limit of the average current as the time interval goes to zero:

$$I = \lim_{\Delta t \to 0} I_{av} = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t}$$

- 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.



In conducting wires

* If a potential difference is applied across the ends of the conductors it sets up a potential difference which gives rise to a source of energy for the charges and leads to a flow of charges

* The charges which make up the current lose energy as they fall through the potential and this energy is deposited in the wire $\Delta U_{charges} = q\Delta V = -\Delta U_{wire}$

* For a constant current the power delivered to whatever the wire is given by $$P = \frac{\Delta U}{\Delta t}(watts)$$

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.

Example

* 2 coulombs of charge pass through the filament of an incandescent lightbulb in 1 second.
  * What is the average current?
  * How many electrons pass into the filament in 5 seconds
  * What total energy is delivered to the filament in this time?
  * What is the average power delivered?

The current in an electron beam in a cathode-ray tube is measured to be 70 μA. How many electrons hit the screen in 5.0 s? ($e = 1.6 \times 10^{-19}$ C)

a. 2.2×10^{11} electrons

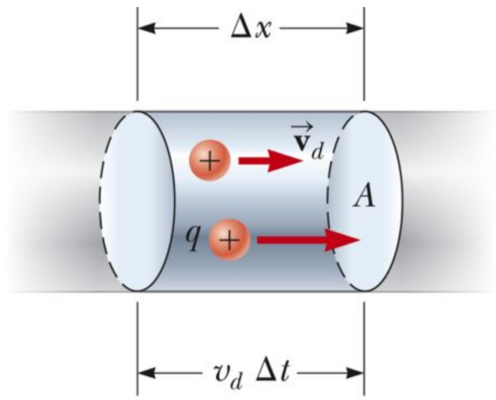
b. 8.8×10^{13} electrons

c. 2.2×10^{15} electrons

d. 8.8×10^{18} electrons

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.

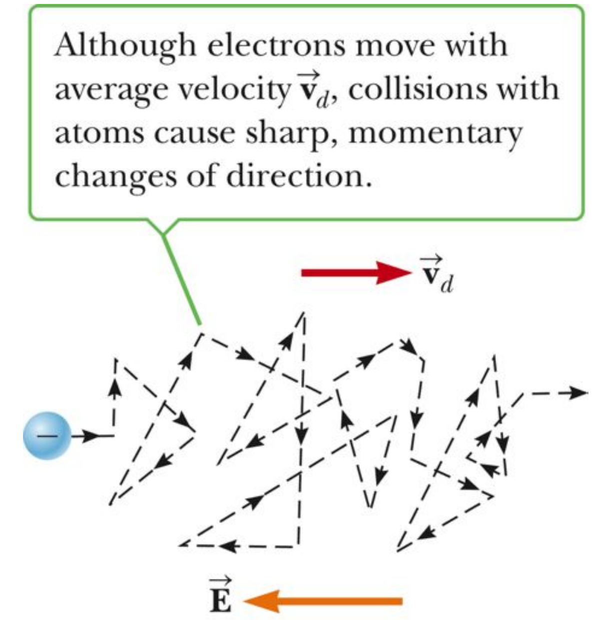
- The total charge is the number of carriers times the charge per carrier, q
  - $\Delta Q = (n\,A\,\Delta x)\,q$
- The drift speed, v_d, is the speed at which the carriers move.
  - $v_d = \Delta x/\Delta t$
- Rewritten: $\Delta Q = (n\,A\,v_d\,\Delta t)\,q$
- Finally, current, $I = \Delta Q/\Delta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

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.



Example

* An aluminum wire has a cross sectional area of 4×10^{-6} m^2 and carries a steady current of 10 Amperes. Aluminum has a density of 2.7g/cm^3
    * Assuming each aluminum atom supplies one electron calculate the drift speed of the electrons
    * Calculate the time it takes one electron to travel 100 kilometers

If the current in a wire is tripled, what effect does this have on the electron drift velocity in the wire?

a.It stays the same.

b.It triples.

c.It decreases by a factor of three.

d.It increases by a factor of nine.

The number density of conduction electrons in a metal can be found from the density rho of the metal, the mass per mole *M* of the metal, the number of conduction electrons per metal atom, and Avogadro's number N_A. If we assume one conduction electron per atom, which of the following gives the number density of conduction electrons for a given metal?

a. N_A rho M

b. N_A rho/M

c. N_A M/rho

d. NA /rho M

A high voltage transmission line of diameter 2 cm and length 200 km carries a steady current of 1 000 A. If the conductor is copper with a free charge density of 8×10^{28} electrons/m^3, how long does it take one electron to travel the full length of the cable? ($e = 1.6 \times 10^{-19}$ C)

a.88 10^2 s

b.8×10^4 s

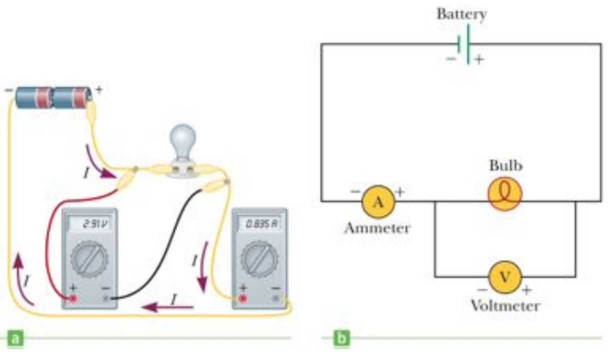
c.8×10^6 s

d.8×10^8 s

Circuits

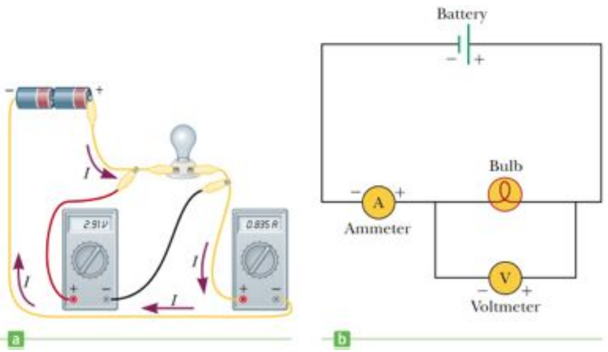
- A circuit is a closed path of some sort around which current circulates.
- A circuit diagram can be used to represent the circuit.
- Quantities of interest are generally current and potential difference.

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.

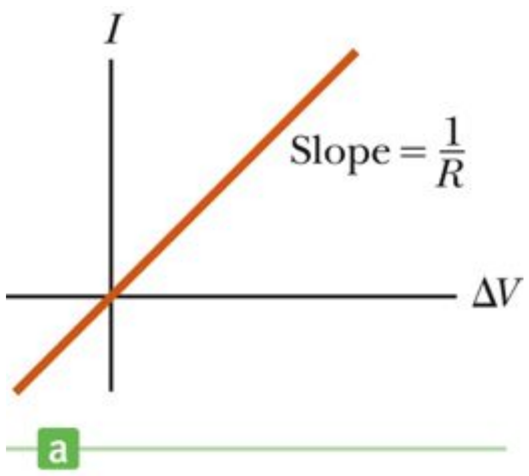
- Units of resistance are *ohms* (Ω)
  - 1 Ω = 1 V / A
- Resistance in a circuit arises due to collisions between the electrons carrying the current with the fixed atoms inside the conductor.

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.*

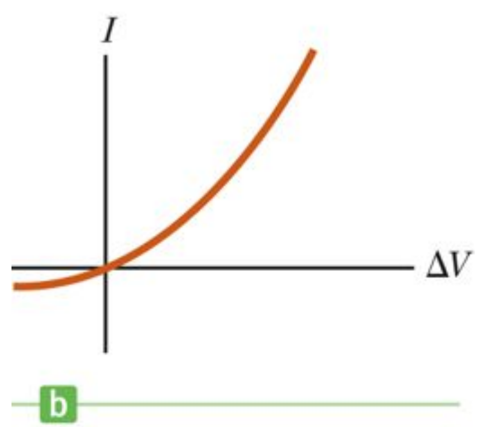
Ohm's Law, Cont.

- 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.



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

Section 17.4

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.

Table 17-1, p. 598

Example

* A potential difference is applied across a 3.2 meter length of wire with uniform radius .4 cm. A current of 4 amperes is produced when the voltage is .00405 volts
    * What is the resistance of the wire?
    * What is the resistivity of the wire?
    * What's the wire made out of?

A flashlight bulb operating at a voltage of 4.5 V has a resistance of 8.0 ohms. How many electrons pass through the bulb filament per second ($e = 1.6 \times 10^{-19}$ C)?

a. 3.7×10^{16}

b. 1.8×10^{21}

c. 9.4×10^{17}

d. 3.5×10^{18}

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
  - α 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.

$$R = R_o[1+\alpha(T-T_o)]$$

Example

* At 20 degrees C the carbon resistor in an electric circuit connected to a 5 volt battery has a resistance of 2×10^2 ohms. What is the current in the circuit when the temperature is 80 degrees C? The alpha coefficient for carbon is -.5 x 10-3

By what factor is the resistance of a copper wire changed when its temperature is increased from 20°C to 120°C? The temperature coefficient of resistivity for copper = 3.9×10^{-3} $(°C)^{-1}$.

a. 0.72

b. 1.06

c. 1.39

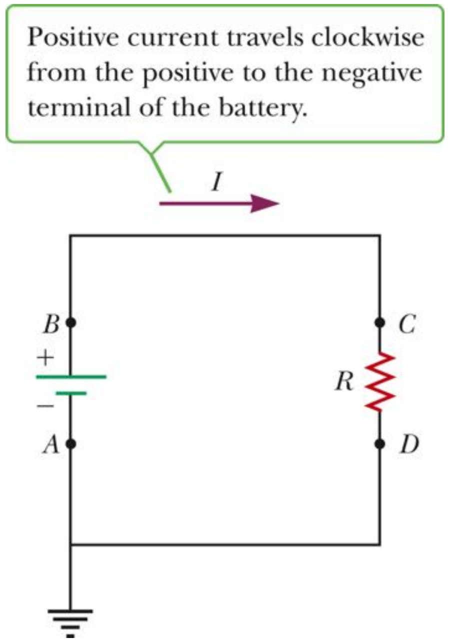
d. 1.44

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 ΔQΔV.
  - 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.

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.



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 ΔQΔV.
  - 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

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

Section 17.6

This power delivered to the wire heats it and is called Joule heating. It is a major source of power loss in transmission lines. Superconductors would allow for more energy efficient power transmission

Electrical Energy and Power, Final

- The SI unit of power is Watt (W).
  - I must be in Amperes, R in ohms and ΔV 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

Example

* Suppose your waffle iron is rated at 1 kW when connected to a 1.2×10^2V source
  * What current does it carry?
  * What is it's resistance?

If a lamp has resistance of 120 ohms when it operates at 100 W, what is the applied voltage?

a. 110 V

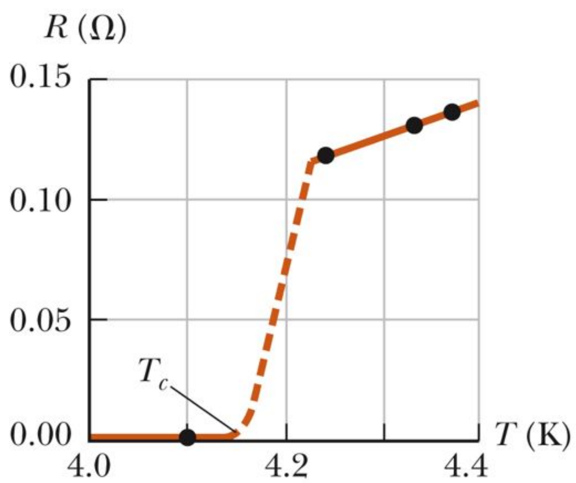
b. 120 V

c. 125 V

d. 220 V

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



Section 17.7

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

Section 17.7

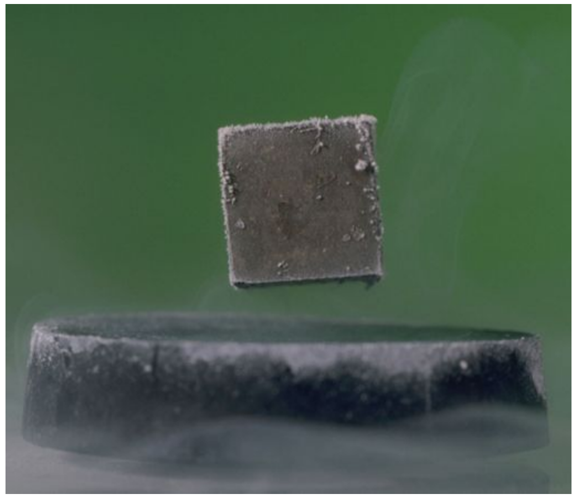
Superconductor Timeline

- 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

Section 17.7

Superconductor, Final

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



Section 17.7

Key Concepts

* Current is defined as the flow of positively charged particles
* Resistance is a measure of how easily current may flow
* Resistivity is different than resistance
* Joule heating causes a loss of energy as a current flows through a resistor
* Power loss in a resistor depends on the resistance, voltage, and current

Key Equations

Average Current $I_{av} = \frac{\Delta Q}{\Delta T}$ Coulombs/s or Amperes

Instantaneous Current $I_{Inst} = \lim_{\Delta t \to 0} I_{av} = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta T}$

$$\Delta Q = (nAv_d \Delta t)q$$

$$I = \lim_{\Delta r \to 0} \frac{\Delta Q}{\Delta t} = (nAv_d)q$$

Resistance $\Delta V = IR \quad \to R = \rho \frac{l}{A}$

$$\rho = \rho_0[1 + \alpha(T - T_0)] \to R = R_0[1 + \alpha(T - T_0)]$$

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