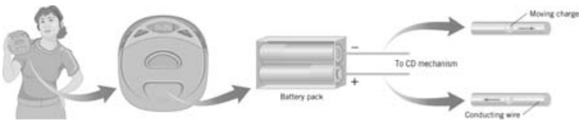
Chapter 20

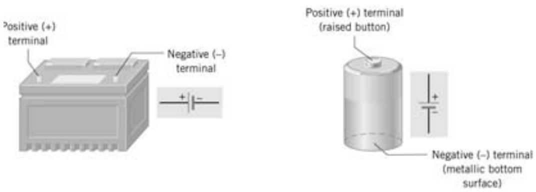
Circuits

In an electric circuit, an energy source and an energy consuming device are connected by conducting wires through which electric charges move.

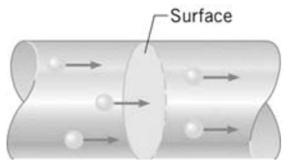


Within a battery, a chemical reaction occurs that transfers electrons from one terminal to another terminal.

The maximum potential difference across the terminals is called the ***electromotive force (emf)***.

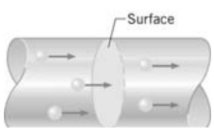


The ***electric current*** is the amount of charge per unit time that passes through a surface that is perpendicular to the motion of the charges.



$$I = \frac{\Delta q}{\Delta t}$$

One coulomb per second equals one ***ampere*** (A).



If the charges move around the circuit in the same direction at all times, the current is said to be ***direct current*** (***dc***).

If the charges move first one way and then the opposite way, the current is said to be ***alternating current*** (***ac***).

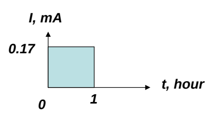
Example 1 **A Pocket Calculator**

The current in a 3.0 V battery of a pocket calculator is 0.17 mA. In one hour of operation, (a) how much charge flows in the circuit and (b) how much energy does the battery deliver to the calculator circuit? (c) Draw a current versus time graph

(a) $\Delta q = I(\Delta t) = (0.17\times 10^{-3}\,\mathrm{A})(3600\,\mathrm{s}) = 0.61\,\mathrm{C}$

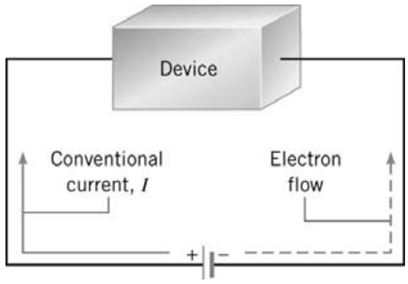
(b) $\mathrm{Energy} = \mathrm{Charge}\times\frac{\mathrm{Energy}}{\mathrm{Charge}} = (0.61\,\mathrm{C})(3.0\,\mathrm{V}) = 1.8\,\mathrm{J}$

(c)



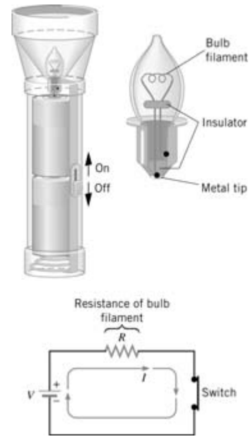
20.1 Electromotive Force and Current

Conventional current is the hypothetical flow of positive charges that would have the same effect in the circuit as the movement of negative charges that actually does occur.



20.2 Ohm's Law

The ***resistance*** (R) is defined as the ratio of the voltage V applied across a piece of material to the current I through the material.



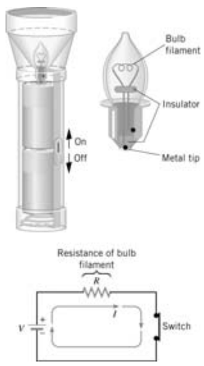
20.2 Ohm's Law

OHM'S LAW

The ratio *V/I* is a constant, where *V* is the voltage applied across a piece of material and *I* is the current through the material:

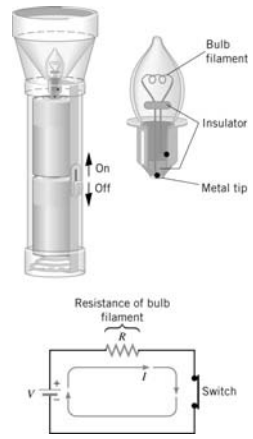
$$\frac{V}{I} = R = \text{constant} \qquad \text{or} \qquad V = IR$$

SI Unit of Resistance: volt/ampere (V/A) = ohm (Ω)



20.2 Ohm's Law

To the extent that a wire or an electrical device offers resistance to electrical flow, it is called a ***resistor.***

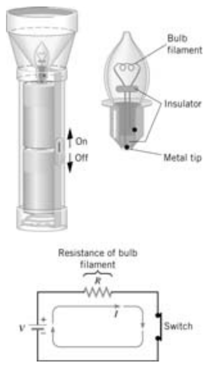


20.2 Ohm's Law

Example 2 **A Flashlight**

The filament in a light bulb is a resistor in the form of a thin piece of wire. The wire becomes hot enough to emit light because of the current in it. The flashlight uses two 1.5-V batteries to provide a current of 0.40 A in the filament. Determine the resistance of the glowing filament.

$$R = \frac{V}{I} = \frac{3.0\ \text{V}}{0.40\ \text{A}} = 7.5\,\Omega$$



20.3 Resistance and Resistivity

For a wide range of materials, the resistance of a piece of material of length *L* and cross-sectional area *A* is

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

resistivity in units of ohm·meter

20.3 Resistance and Resistivity

Table 20.1 Resistivities[a] of Various Materials

Material	Resistivity ρ ($\Omega \cdot m$)	Material	Resistivity ρ ($\Omega \cdot m$)
Conductors		***Semiconductors***	
Aluminum	2.82×10^{-8}	Carbon	3.5×10^{-5}
Copper	1.72×10^{-8}	Germanium	0.5[b]
Gold	2.44×10^{-8}	Silicon	$20-2300$[b]
Iron	9.7×10^{-8}	***Insulators***	
Mercury	95.8×10^{-8}	Mica	$10^{11}-10^{15}$
Nichrome (alloy)	100×10^{-8}	Rubber (hard)	$10^{13}-10^{16}$
Silver	1.59×10^{-8}	Teflon	10^{16}
Tungsten	5.6×10^{-8}	Wood (maple)	3×10^{10}

[a] The values pertain to temperatures near 20 °C.
[b] Depending on purity.

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

20.3 Resistance and Resistivity

Example 3 **Longer Extension Cords**

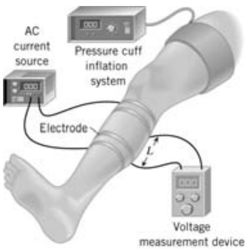
The instructions for an electric lawn mower suggest that a 20-gauge extension cord can be used for distances up to 35 m, but a thicker 16-gauge cord should be used for longer distances. The cross sectional area of a 20-gauge wire is $5.2\times10^{-7}\Omega\cdot m$, while that of a 16-gauge wire is $13\times10^{-7}\Omega\cdot m$. Determine the resistance of (a) 35 m of 20-gauge copper wire and (b) 75 m of 16-gauge copper wire.

(a) $$R = \rho \frac{L}{A} = \frac{(1.72\times10^{-8}\,\Omega\cdot\text{m})(35\,\text{m})}{5.2\times10^{-7}\,\text{m}^2} = 1.2\,\Omega$$

(b) $$R = \rho \frac{L}{A} = \frac{(1.72\times10^{-8}\,\Omega\cdot\text{m})(75\,\text{m})}{13\times10^{-7}\,\text{m}^2} = 0.99\,\Omega$$

20.3 Resistance and Resistivity

Impedance Plethysmography.



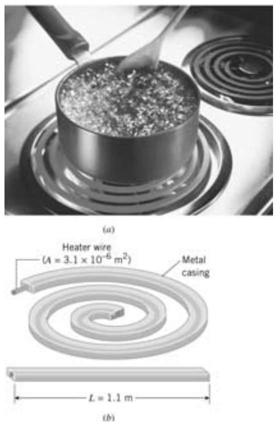
$$R = \rho \frac{L}{A} = \rho \frac{L}{V_{\text{calf}}/L} = \rho \frac{L^2}{V_{\text{calf}}}$$

20.3 Resistance and Resistivity

$$\rho = \rho_o\left[1 + \alpha\left(T - T_o\right)\right]$$

temperature coefficient of resistivity

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



20.4 Electric Power

Suppose some charge emerges from a battery and the potential difference between the battery terminals is *V*.

$$P = \frac{(\Delta q)V}{\Delta t} = \frac{\Delta q}{\Delta t} V = IV$$

energy

power

time

20.4 Electric Power

ELECTRIC POWER

When there is current in a circuit as a result of a voltage, the electric power delivered to the circuit is:

$$P = IV$$

SI Unit of Power: watt (W)

Many electrical devices are essentially resistors:

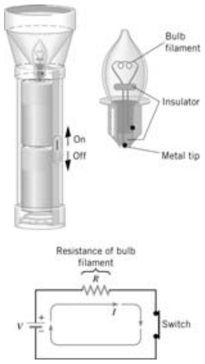
$$P = I(IR) = I^2R$$

$$P = \left(\frac{V}{R}\right)V = \frac{V^2}{R}$$

20.4 Electric Power

Example 5 **The Power and Energy Used in a Flashlight**

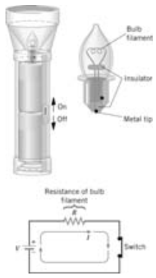
In the flashlight, the current is 0.40A and the voltage is 3.0 V. Find (a) the power delivered to the bulb and (b) the energy dissipated in the bulb in 5.5 minutes of operation.



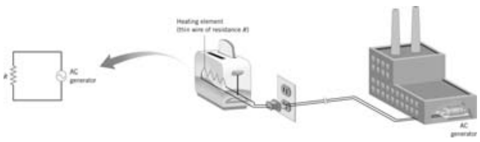
20.4 Electric Power

(a) $P = IV = (0.40\ \text{A})(3.0\ \text{V}) = 1.2\ \text{W}$

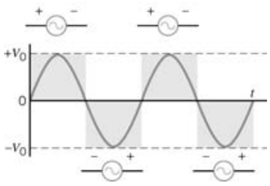
(b) $E = Pt = (1.2\ \text{W})(330\ \text{s}) = 4.0\times10^{2}\ \text{J}$



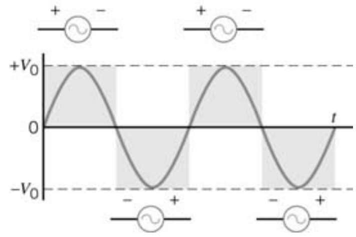
20.5 Alternating Current



In an AC circuit, the charge flow reverses direction periodically.



20.5 Alternating Current

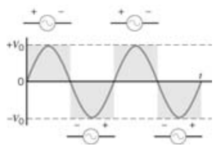


$$V = V_o \sin(2\pi\, ft)$$

peak voltage

20.5 Alternating Current

In circuits that contain only resistance, the current reverses direction each time the polarity of the generator reverses.



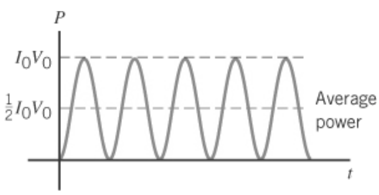
$$I = \frac{V}{R} = \frac{V_o}{R}\sin(2\pi\, ft) = I_o \sin(2\pi\, ft)$$

peak current

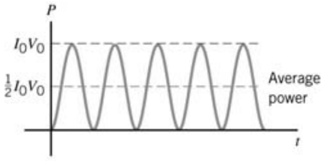
20.5 Alternating Current

$I = I_o \sin(2\pi\, ft)$ $\qquad$ $V = V_o \sin(2\pi\, ft)$

$$P = IV = I_o V_o \sin^2(2\pi\, ft)$$



20.5 Alternating Current



$$\overline{P} = \frac{I_o V_o}{2} = \left(\frac{I_o}{\sqrt{2}}\right)\left(\frac{V_o}{\sqrt{2}}\right) = I_{\text{rms}} V_{\text{rms}}$$

20.5 Alternating Current

$$V_{\text{rms}} = I_{\text{rms}} R$$

$$\overline{P} = V_{\text{rms}} I_{\text{rms}}$$

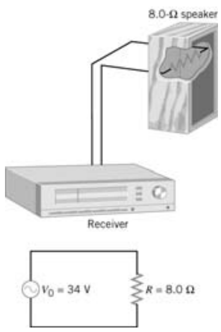
$$\overline{P} = I_{\text{rms}}^2 R$$

$$\overline{P} = \frac{V_{\text{rms}}^2}{R}$$

20.5 Alternating Current

Example 6 **Electrical Power Sent to a Loudspeaker**

A stereo receiver applies a peak voltage of 34 V to a speaker. The speaker behaves approximately as if it had a resistance of 8.0 Ω. Determine (a) the rms voltage, (b) the rms current, and (c) the average power for this circuit.

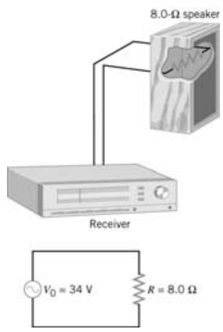


20.5 Alternating Current

(a) $V_{\text{rms}} = \frac{V_o}{\sqrt{2}} = \frac{34\text{ V}}{\sqrt{2}} = 24\text{ V}$

(b) $I_{\text{rms}} = \frac{V_{\text{rms}}}{R} = \frac{24\text{ V}}{8.0\,\Omega} = 3.0\text{ A}$

(c) $\overline{P} = I_{\text{rms}} V_{\text{rms}} = (3.0\text{ A})(24\text{ V}) = 72\text{ W}$



20.5 Alternating Current

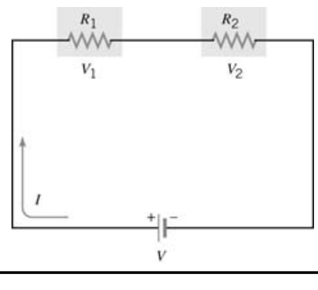
Conceptual Example 7 **Extension Cords and a Potential Fire Hazard**

During the winter, many people use portable electric space heaters to keep warm. Sometimes, however, the heater must be located far from a 120-V wall receptacle, so an extension cord must be used. However, manufacturers often warn against using an extension cord. If one must be used, they recommend a certain wire gauge, or smaller. Why the warning, and why are smaller-gauge wires better then larger-gauge wires?

20.6 Series Wiring

There are many circuits in which more than one device is connected to a voltage source.

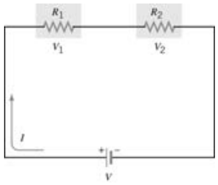
Series wiring means that the devices are connected in such a way that there is the same electric current (same amount of charges in one second) through each device.



20.6 Series Wiring

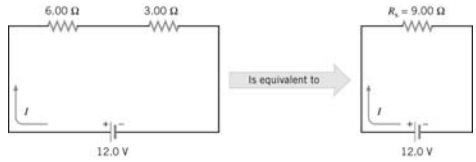
Total potential drop in a series circuit is

$$V = V_1 + V_2 = IR_1 + IR_2 = I(R_1 + R_2) = IR_S$$



Series resistors $R_S = R_1 + R_2 + R_3 + \cdots$

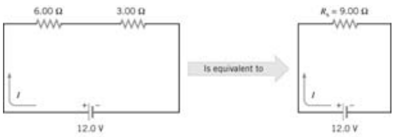
20.6 Series Wiring



Example 8 **Resistors in a Series Circuit**

A 6.00 Ω resistor and a 3.00 Ω resistor are connected in series with a 12.0 V battery. Assuming the battery contributes no resistance to the circuit, find (a) the current, (b) the power dissipated in each resistor, and (c) the total power delivered to the resistors by the battery.

20.6 Series Wiring



(a) $R_S = 6.00\,\Omega + 3.00\,\Omega = 9.00\,\Omega$ $\qquad I = \dfrac{V}{R_S} = \dfrac{12.0\text{ V}}{9.00\,\Omega} = 1.33\text{ A}$

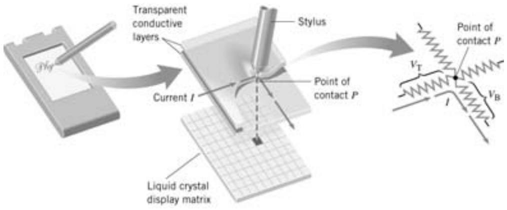
(b) $P = I^2R = (1.33\text{ A})^2(6.00\,\Omega) = 10.6\text{ W}$

$P = I^2R = (1.33\text{ A})^2(3.00\,\Omega) = 5.31\text{ W}$

(c) $P = 10.6\text{ W} + 5.31\text{ W} = 15.9\text{ W}$

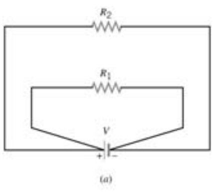
20.6 Series Wiring

Personal electronic assistants.



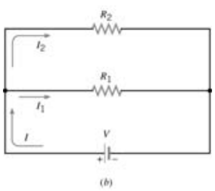
20.7 Parallel Wiring

Parallel wiring means that the devices are connected in such a way that the same voltage is applied across each device.

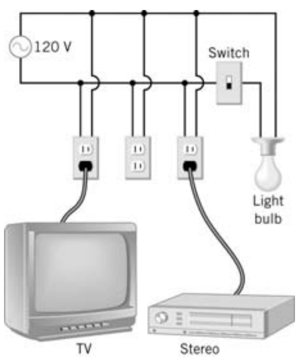


When two resistors are connected in parallel, each receives current from the battery as if the other was not present.

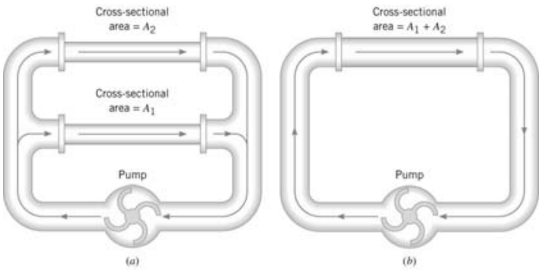
Therefore the two resistors connected in parallel draw more current than does either resistor alone.



20.7 Parallel Wiring



20.7 Parallel Wiring



The two parallel pipe sections are equivalent to a single pipe of the same length and same total cross sectional area.

20.7 Parallel Wiring

Total current in a parallel circuit is:

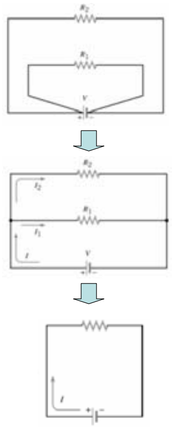
$$I = I_1 + I_2 = \frac{V}{R_1} + \frac{V}{R_2} = V\left(\frac{1}{R_1} + \frac{1}{R_2}\right) = V\left(\frac{1}{R_P}\right)$$

Then $$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} = \frac{R_2}{R_1R_2} + \frac{R_1}{R_2R_1}$$

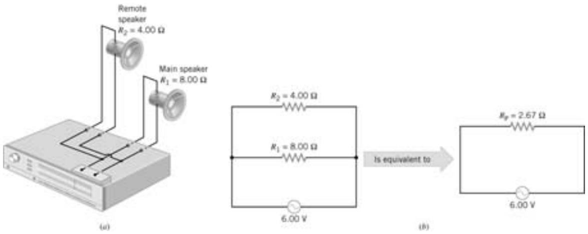
Hence $$R_P = \frac{R_1R_2}{R_1 + R_2}$$

For many resistors in parallel

$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$



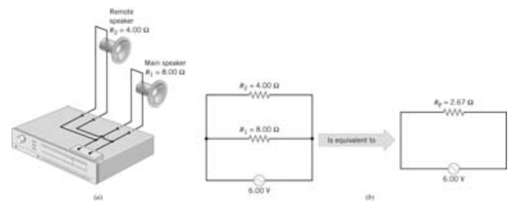
20.7 Parallel Wiring



Example 10 **Main and Remote Stereo Speakers**

Most receivers allow the user to connect to "remote" speakers in addition to the main speakers. At the instant represented in the picture, the voltage across the speakers is 6.00 V. Determine (a) the equivalent resistance of the two speakers, (b) the total current supplied by the receiver, (c) the current in each speaker, and (d) the power dissipated in each speaker.

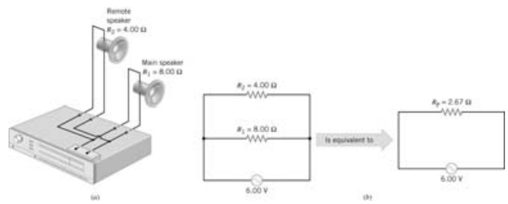
20.7 Parallel Wiring



(a) $$\frac{1}{R_P} = \frac{1}{8.00\,\Omega} + \frac{1}{4.00\,\Omega} = \frac{3}{8.00\,\Omega}$$ $$R_P = 2.67\,\Omega$$

(b) $$I_{\text{rms}} = \frac{V_{\text{rms}}}{R_P} = \frac{6.00\text{ V}}{2.67\,\Omega} = 2.25\text{ A}$$

20.7 Parallel Wiring



(c) $$I_{\text{rms}} = \frac{V_{\text{rms}}}{R} = \frac{6.00\text{ V}}{8.00\,\Omega} = 0.750\text{ A} \qquad I_{\text{rms}} = \frac{V_{\text{rms}}}{R} = \frac{6.00\text{ V}}{4.00\,\Omega} = 1.50\text{ A}$$

(d) $$\overline{P} = I_{\text{rms}}V_{\text{rms}} = (0.750\text{ A})(6.00\text{ V}) = 4.50\text{ W}$$

$$\overline{P} = I_{\text{rms}}V_{\text{rms}} = (1.50\text{ A})(6.00\text{ V}) = 9.00\text{ W}$$

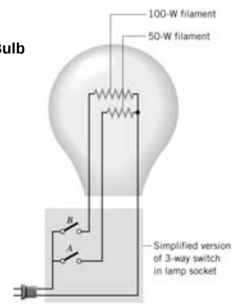
20.7 Parallel Wiring

Conceptual Example 11 **A Three-Way Light Bulb and Parallel Wiring**

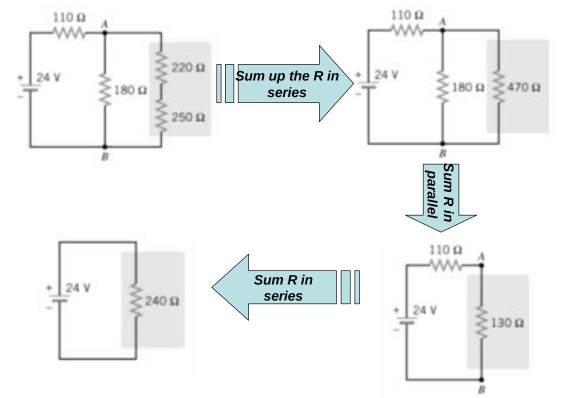
Within the bulb there are two separate filaments. When one burns out, the bulb can produce only one level of illumination, but not the highest.

Are the filaments connected in series or parallel?

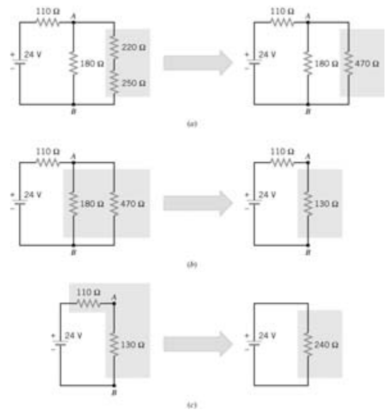
How can two filaments be used to produce three different illumination levels?



20.8 Circuits Wired Partially in Series and Partially in Parallel



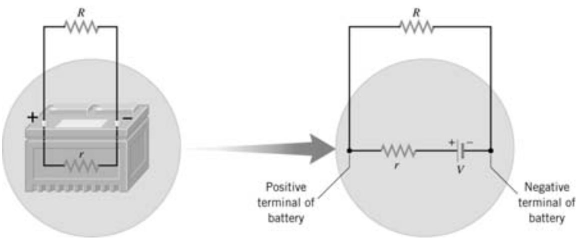
20.8 Circuits Wired Partially in Series and Partially in Parallel



20.9 Internal Resistance

Batteries and generators add some resistance to a circuit. This resistance is called ***internal resistance.***

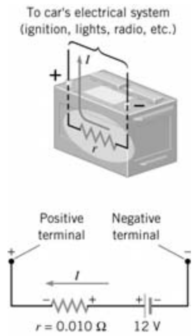
The actual voltage between the terminals of a batter is known as the ***terminal voltage.***



20.9 Internal Resistance

Example 12 **The Terminal Voltage of a Battery**

The car battery has an emf of 12.0 V and an internal resistance of 0.0100 Ω. What is the terminal voltage when the current drawn from the battery is (a) 10.0 A and (b) 100.0 A?



(a) $V = Ir = (10.0\ \text{A})(0.010\ \Omega) = 0.10\ \text{V}$

$$12.0\ \text{V} - 0.10\ \text{V} = 11.9\text{V}$$

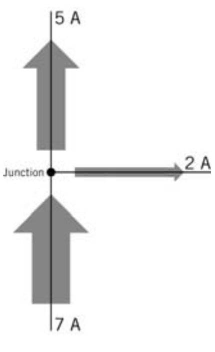
(b) $V = Ir = (100.0\ \text{A})(0.010\ \Omega) = 1.0\ \text{V}$

$$12.0\ \text{V} - 1.0\ \text{V} = 11.0\text{V}$$

20.10 Kirchhoff's Rules

The junction rule states that the total current directed into a junction must equal the total current directed out of the junction.

$$\sum I_{in} = \sum I_{out} \quad 7\ A = 2\ A + 5\ A$$



20.10 Kirchhoff's Rules

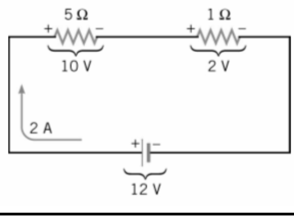
The loop rule expresses conservation of energy in terms of the electric potential and states that for a closed circuit loop, the total of all potential rises is the same as the total of all potential drops.

1. ***In a loop, choose either clockwise or counterclockwise.***
2. ***Label the high and low potential region by the + and – signs. (note that once you choose the direction of current, then it flows from the high (+) to the low (-) potential region)***
3. ***Use Kirchhoff's loop rule***

$$\sum V_{drop} = \sum V_{rise}$$

$$5I + I = 12$$

$$6I = 12.\ So\ I = 2\ A$$



20.10 Kirchhoff's Rules

KIRCHHOFF'S RULES

Junction rule. The sum of the magnitudes of the currents directed into a junction equals the sum of the magnitudes of the currents directed out of a junction.

$$\sum I_{in} = \sum I_{out}$$

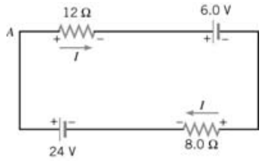
Loop rule. Around any closed circuit loop, the sum of the potential drops equals the sum of the potential rises.

$$\sum V_{drop} = \sum V_{rise}$$

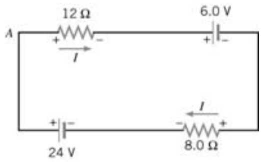
20.10 Kirchhoff's Rules

Example 14 **Using Kirchhoff's Loop Rule**

Determine the current in the circuit.



20.10 Kirchhoff's Rules



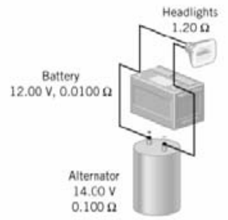
Using clockwise loop

$$\underbrace{I(12\,\Omega) + 6.0\text{ V} + I(8.0\,\Omega)}_{\text{potential drops}} = \underbrace{24\text{ V}}_{\text{potential rises}}$$

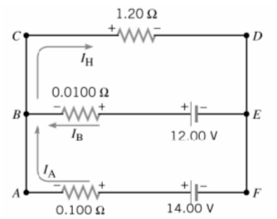
$$I = 0.90\text{ A}$$

20.10 Kirchhoff's Rules- example

Circuit of a car headlight



Circuit diagram



$\sum I_{in} = \sum I_{out}$ At junction B, $I_A + I_B = I_H$

$\sum V_{drop} = \sum V_{rise}$ Loop BCDA $(1.20\Omega)I_H + (0.01\Omega)I_B = 12\,V$

Loop ABEF $12\,V + (0.10\Omega)I_A = (0.01\Omega)I_B + 14\,V$

20.10 Kirchhoff's Rules

Reasoning Strategy

Applying Kirchhoff's Rules

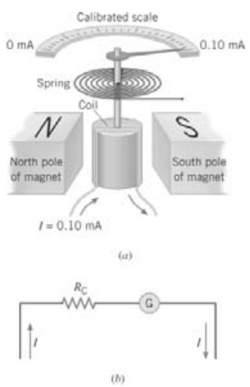
1. Draw the current in each branch of the circuit. Choose any direction. If your choice is incorrect, the value obtained for the current will turn out to be a negative number.

2. Mark each resistor with a + at one end and a – at the other end in a way that is consistent with your choice for current direction in step 1. Outside a battery, conventional current is always directed from a higher potential (the end marked +) to a lower potential (the end marked -).

3. Apply the junction rule and the loop rule to the circuit, obtaining in the process as many independent equations as there are unknown variables.

4. Solve these equations simultaneously for the unknown variables.

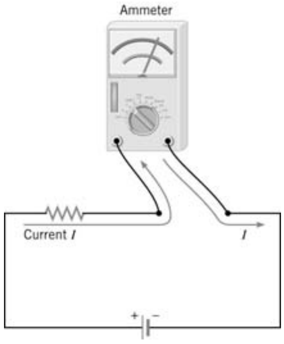
20.11 The Measurement of Current and Voltage



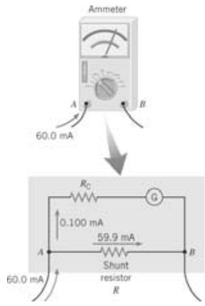
A dc galvanometer. The coil of wire and pointer rotate when there is a current in the wire.

20.11 The Measurement of Current and Voltage

An ammeter must be inserted into a circuit so that the current passes directly through it.

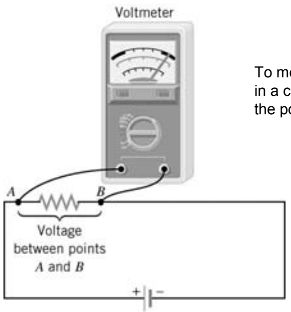


20.11 The Measurement of Current and Voltage



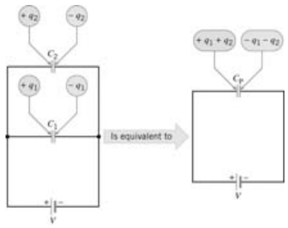
If a galvanometer with a full-scale limit of 0.100 mA is to be used to measure the current of 60.0 mA, a shunt resistance must be used so that the excess current of 59.9 mA can detour around the galvanometer coil.

20.11 The Measurement of Current and Voltage



To measure the voltage between two points in a circuit, a voltmeter is connected between the points.

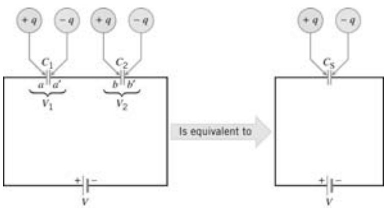
20.12 Capacitors in Series and Parallel



$$q = q_1 + q_2 = C_1V + C_2V = (C_1 + C_2)V$$

Parallel capacitors $$C_P = C_1 + C_2 + C_3 + \cdots$$

20.12 Capacitors in Series and Parallel



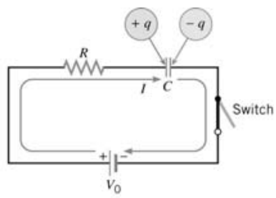
$$V = V_1 + V_2 = \frac{q}{C_1} + \frac{q}{C_2} = q\left(\frac{1}{C_1} + \frac{1}{C_2}\right)$$

Series capacitors $$\frac{1}{C_S} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \cdots$$

20.13 RC Circuits

Capacitor charging

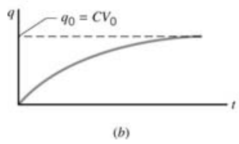
$$q = q_o\left[1 - e^{-t/RC}\right]$$



(a)

time constant

$$\tau = RC$$

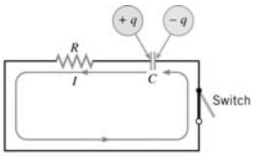


(b)

20.13 RC Circuits

Capacitor discharging

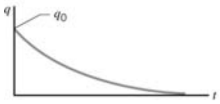
$$q = q_o e^{-t/RC}$$



(a)

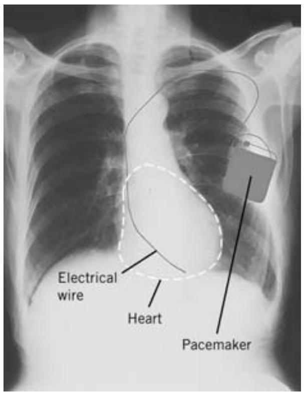
time constant

$$\tau = RC$$



(b)

20.13 RC Circuits



20.14 Safety and the Physiological Effects of Current

To reduce the danger inherent in using circuits, proper ***electrical grounding*** is necessary.