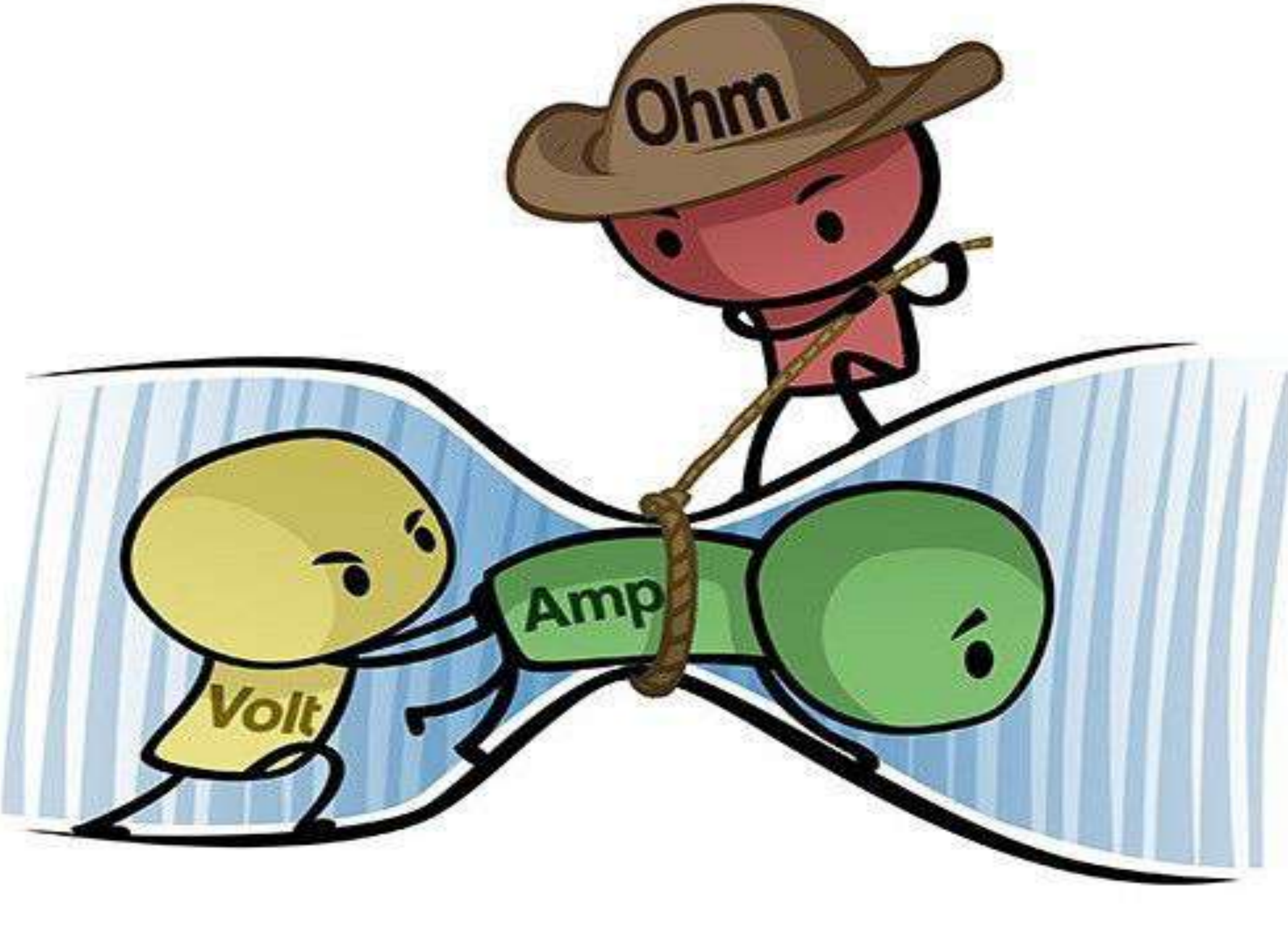
Ch.27: Current and Resistance



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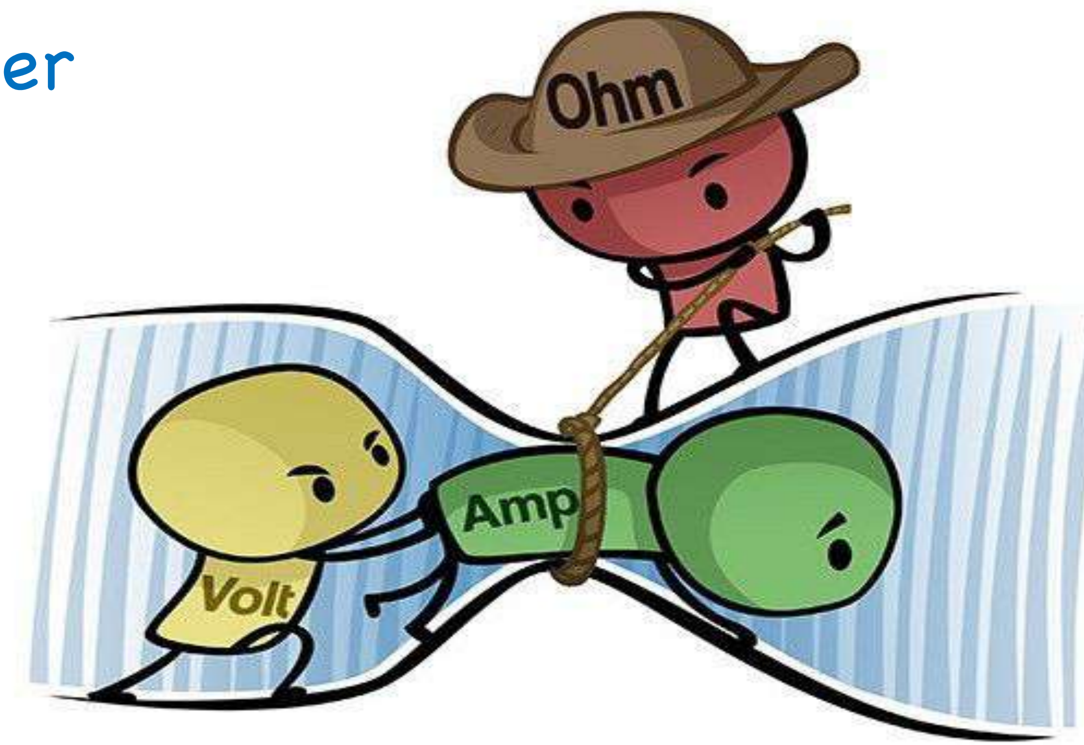
Chapter Outline

27.1 Electric Current

27.2 Resistance

27.4 Resistance and Temperature

27.6 Electrical Power



Introduction:

- ✓ So far, we have been studying the features of the electric charges when they were "still -or- not moving". This is called **Electrostatic** situation.
- ✓ Now we move to the situation when the charges move due to an external force. This is called **Electrodynamic** situation.
- ✓ In this situation, we maintain the electric field by an external source "battery" within a conductor, and the conductor forms a complete circuit.
- ✓ The electric field will apply force on the charges within the conductor.
- ✓ Positive charges are heavy, so they don't really move.
- ✓ Electrons are much lighter, so they are the ones that move when field is applied.

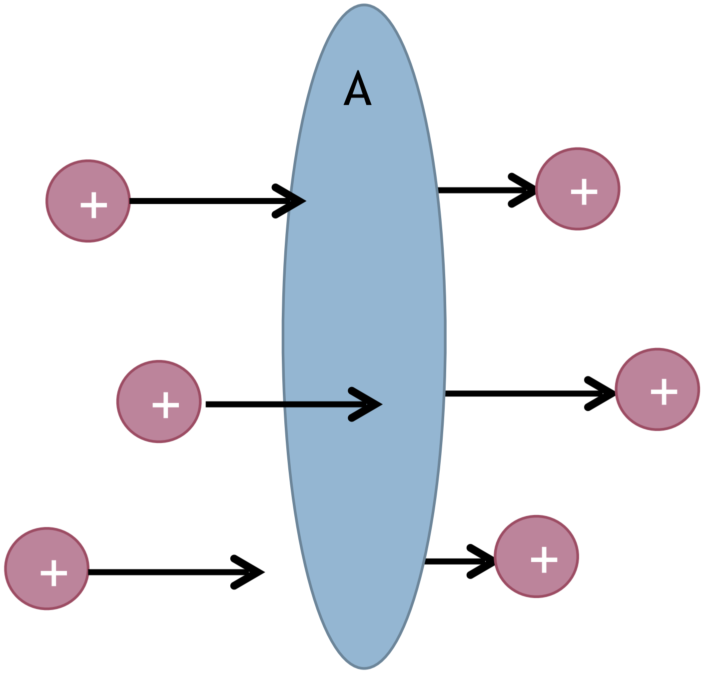
Electric Current (I):

Definition: The electric current (I) is the rate at which charge flows through a surface.

(Rate = number of something per time).

The average current is the amount of charge that passes through surface A per unit time.

$$I_{av} = \frac{\Delta Q}{\Delta t}$$



The instant current is:

$$I = \frac{dQ}{dt}$$

Current SI Unit: Ampere (A)

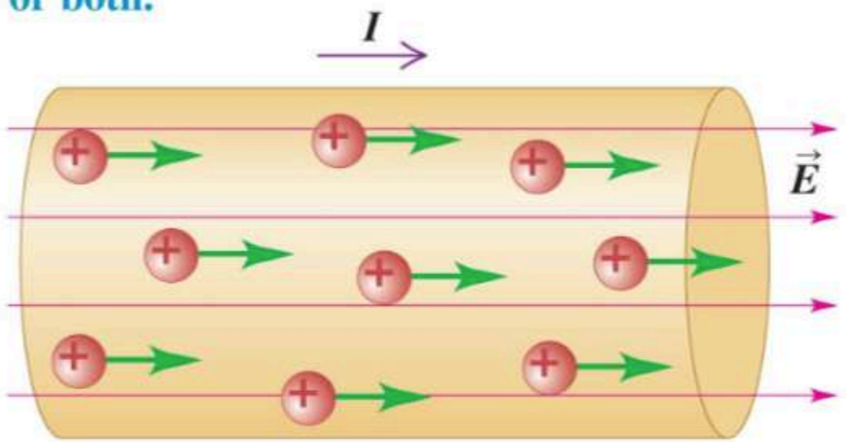
$$1\ \text{A} = \frac{1\ \text{C}}{1\ \text{s}}$$

Electric Current (I):

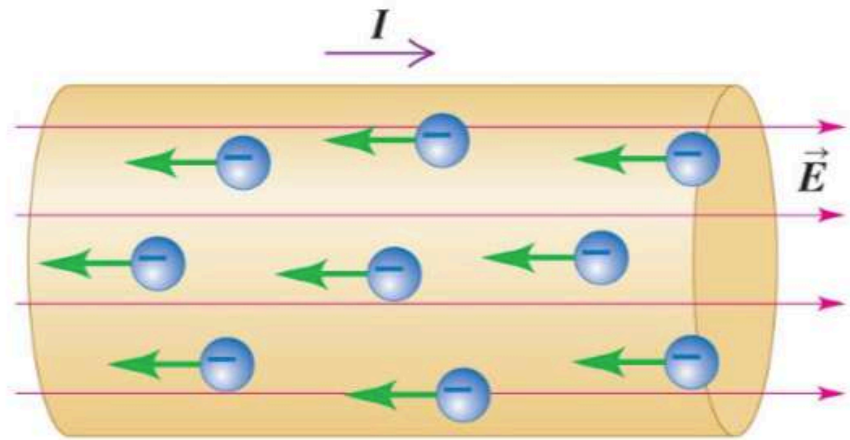
Current Direction:

- The convention is the assign the direction of the current similar to the flow of positive charges.
- The direction of the current is opposite the direction of the electrons flow.
- The moving charge is called **mobile charge carrier**. For metals, the electrons are the mobile charge carriers.

A conventional current is treated as a flow of positive charges, regardless of whether the free charges in the conductor are positive, negative, or both.

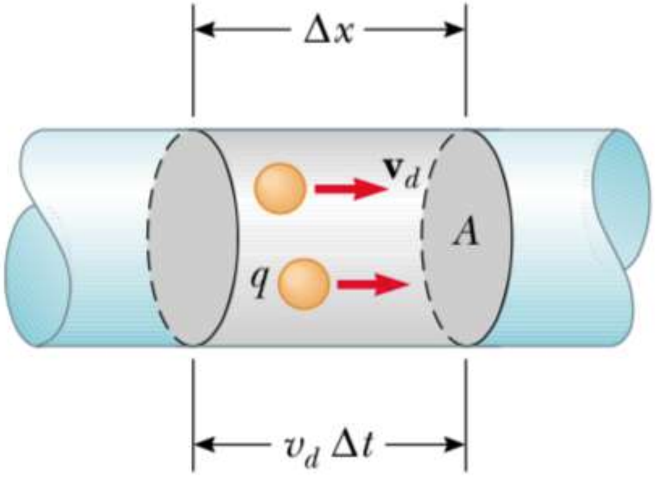


In a metallic conductor, the moving charges are electrons — but the *current* still points in the direction positive charges would flow.



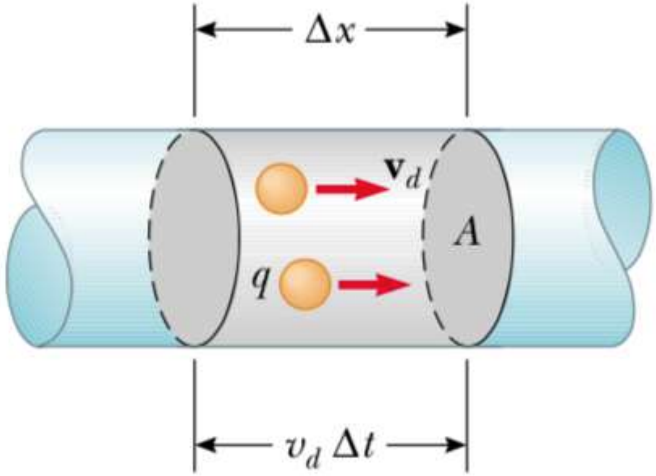
Electric Current (I):

Microscopic Model of Current:



Electric Current (I):

Microscopic Model of Current:



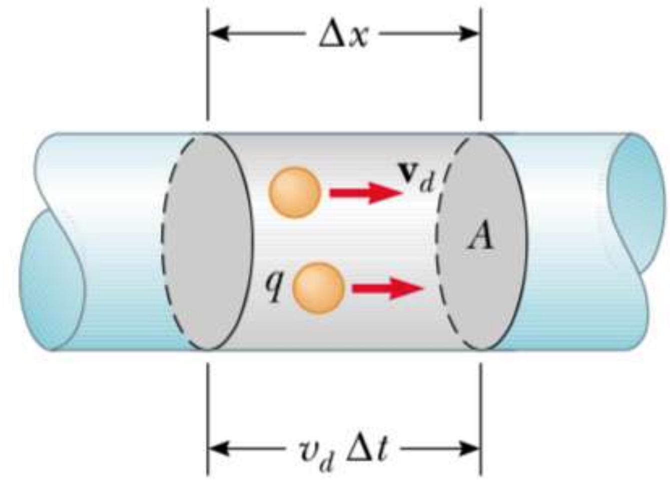
- Assume that the conductor has a cross section area A, then the volume of the section that has a length Δx is $(A\,\Delta x)$.
- If the number of the mobile charge carrier per unit volume is *n* (charge carrier density), the number of the carriers in the gray section is $(n\,A\,\Delta x)$.
- The total charge in this section is then:

$$\Delta Q = \text{number of carriers in section x charge per carrier}$$

$$\Delta Q = (nA\,\Delta x)q$$

Electric Current (I):

Microscopic Model of Current:



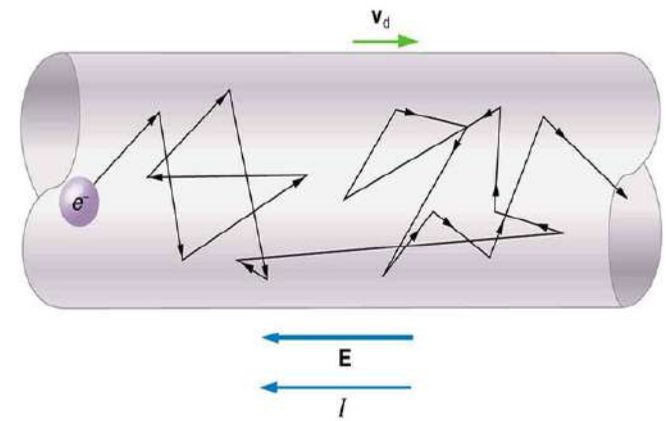
$$\Delta Q = (nA\,\Delta x)q$$

$$\Delta x = v_d \Delta t$$ [displacement = velocity x time]

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

- Dividing both equations by Δt we get:

$$I_{av} = \frac{\Delta Q}{\Delta t} = nAv_d q$$



- v_d is called **Drift Velocity** (is the average velocity that a particle, such an electron, attains in a material due to an electric field). When there is no field, the electrons will move randomly and the average velocity = 0.

Example 27.1 Drift Speed in a Copper Wire

The 12-gauge copper wire in a typical residential building has a cross-sectional area of $3.31 \times 10^{-6}\ m^2$. If it carries a current of 10.0 A, what is the drift speed of the electrons? Assume that each copper atom contributes one free electron to the current. The density of copper is $8.95\ g/cm^3$.

Molar mass of Copper is: 63.5 g (= 1 mol)

Avogadro's number = 6.022×10^{23}

Resistance (R):

Definition: The Current Density (J) is the current per unit area:

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$$I = nAv_d q \longrightarrow J = \frac{I}{A} = nqv_d$$

Current Density SI Unit: Ampere/meter^2 (A/m^2)

The current density is a vector, and the general form is:

$$\vec{J} = nq\vec{v}_d$$

Another form is:

$$\vec{J} \propto \vec{E} \longrightarrow \vec{J} = \sigma \vec{E}$$

Ohm's Law

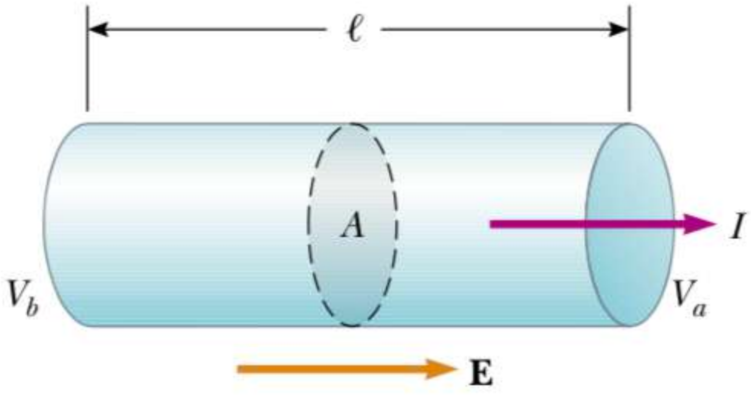
σ : constant called conductivity

Ohm's Law: For any material, the ratio of the current density to the electric field is a constant σ that is independent of the electric field producing the current

Note: Not all materials obey Ohm's law. Materials that obey Ohm's law are called ohmic materials, and the ones that doesn't obey it are called nonohmic materials.

Resistance (R):

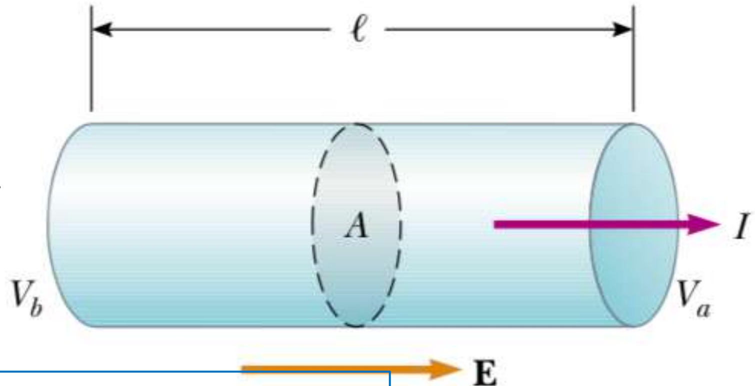
Different form of Ohm's Law:



Resistance (R):

Different form of Ohm's Law:

The potential difference between the two ends of the conductor:



$$\Delta V = V_b - V_a = El$$

(remember in Ch25: $\Delta V = Ed$)

$$J = \sigma E = \sigma \frac{\Delta V}{l}$$

$$\Delta V = \frac{l}{\sigma} J = \frac{l}{\sigma A} I \longrightarrow \boxed{\Delta V = R\, I} \longrightarrow \boxed{R = \frac{\Delta V}{I}}$$

$J = \frac{I}{A}$

$\frac{l}{\sigma A}$: R (resistance)

Ohm's Law

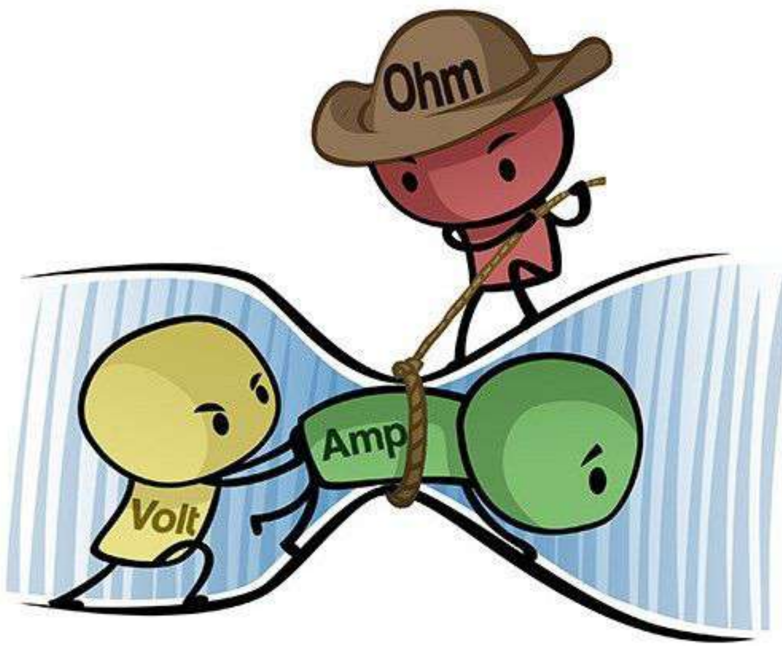
Resistance SI Unit: Ohm (Ω) = 1 Volt/ Ampere

$$1\ \Omega = \frac{1\ \text{V}}{1\ \text{A}}$$

Resistance (R):

How to imagine the relationship between current, potential and resistance:

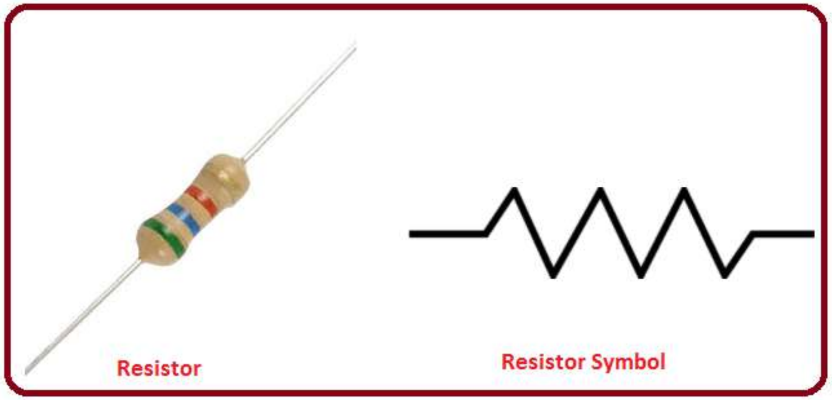
$$R = \frac{\Delta V}{I}$$



The resistance is a feature of the material, it reflects how much the material *resists* the charge passing through it.

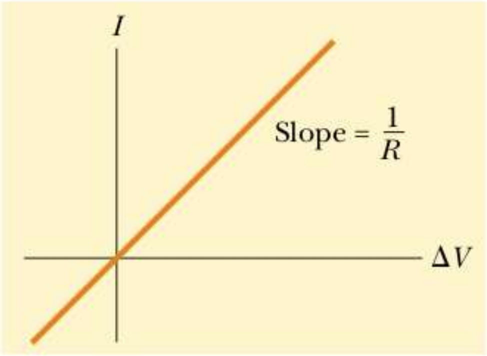
Resistors

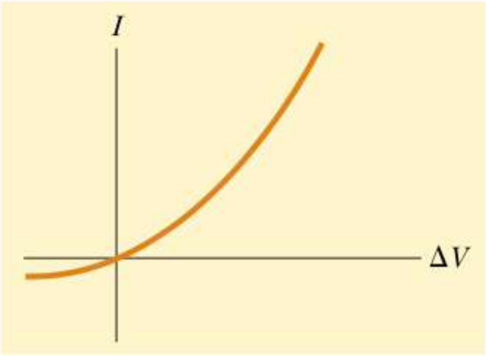
All circuits include what is called “**Resistors**”. The resistors control the current level in the various parts of the circuit.



Ohmic material

Nonohmic material





Useful Quantity: Resistivity (ρ) is the inverse of conductivity σ

$$\rho = \frac{1}{\sigma}$$

We know that:

$$R = \frac{l}{\sigma A} \longrightarrow \boxed{R = \frac{l}{A}\rho} \longrightarrow \boxed{\rho = \frac{A}{l}R}$$

Resistivity SI Unit: Ohm.m (Ω.m)

Note: DO NOT confuse ρ and σ with the volume and surface charge density we took in Ch25! They are different quantities.

The Resistance of a Conductor

Calculate the resistance of an aluminum cylinder that has a length of 10.0 cm and a cross-sectional area of $2.00 \times 10^{-4}\ \text{m}^2$. Repeat the calculation for a cylinder of the same dimensions and made of glass having a resistivity of $3.0 \times 10^{10}\ \Omega \cdot \text{m}$.

Example 27.2 The Resistance of Nichrome Wire

The radius of 22-gauge Nichrome wire is 0.32 mm.

(A) Calculate the resistance per unit length of this wire.

(B) If a potential difference of 10 V is maintained across a 1.0-m length of the Nichrome wire, what is the current in the wire?

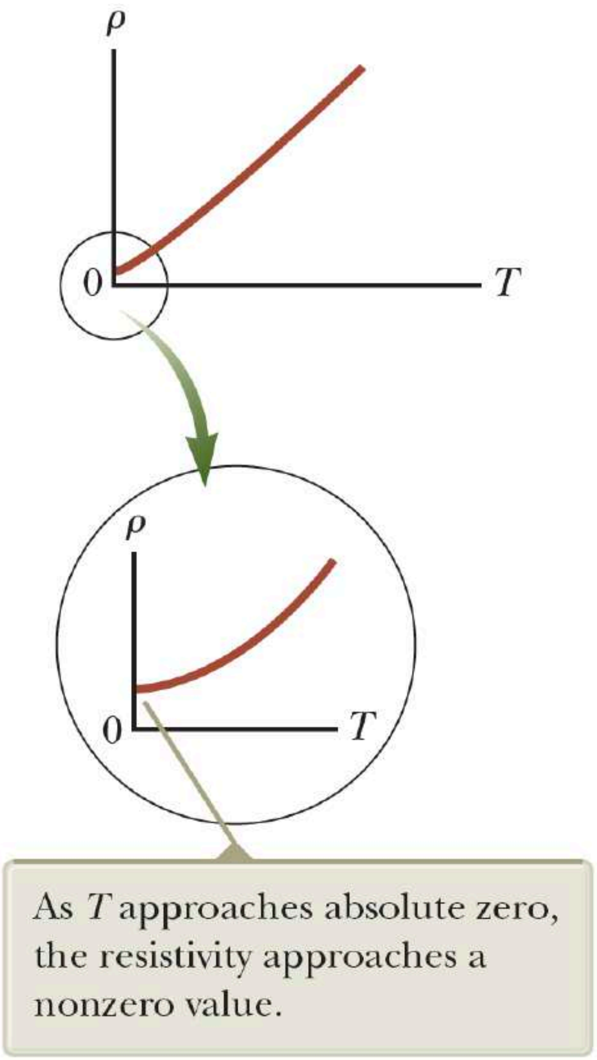
Resistivities and Temperature Coefficients of Resistivity for Various Materials

Material	Resistivity[a] $(\Omega \cdot m)$	Temperature Coefficient[b] $\alpha[(°C)^{-1}]$
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	10×10^{-8}	5.0×10^{-3}
Platinum	11×10^{-8}	3.92×10^{-3}
Lead	22×10^{-8}	3.9×10^{-3}
Nichrome[c]	1.50×10^{-6}	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} to 10^{14}	
Hard rubber	$\sim 10^{13}$	
Sulfur	10^{15}	
Quartz (fused)	75×10^{16}	

Resistance (R) and Temperature (T):

Assume that at a temperature $T_0 = 20^oC$ the resistivity for the conductor was ρ_0 . When we increase the temperature to T, the resistivity will also change according to the formula:

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



α is a constant called the **temperature coefficient of resistivity**

$$\alpha = \frac{1}{\rho_0}\frac{\Delta\rho}{\Delta T}$$

The resistance R will also change with temperature according to:

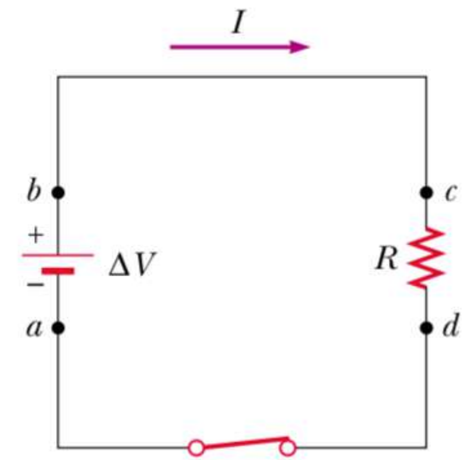
$$R = R_0[1 + \alpha(T - T_0)]$$

Example 27.6 A Platinum Resistance Thermometer

A resistance thermometer, which measures temperature by measuring the change in resistance of a conductor, is made from platinum and has a resistance of 50.0 Ω at 20.0°C. When immersed in a vessel containing melting indium, its resistance increases to 76.8 Ω. Calculate the melting point of the indium.

Electrical Power

Electrical Power

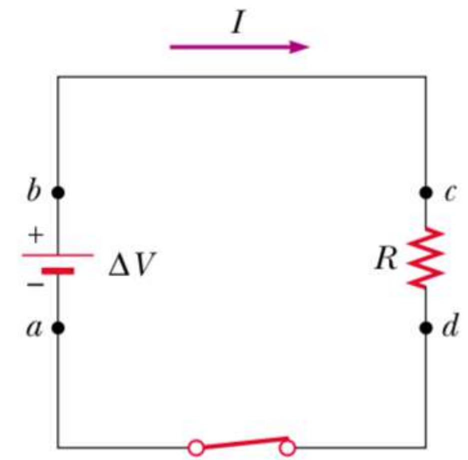


After connecting the battery, the charges will move in the resistor and cause a change in the electric potential by:

$$\Delta U = Q \, \Delta V$$

The electric power P unit is Watt

Electrical Power



After connecting the battery, the charges will move in the resistor and cause a change in the electric potential by:

$$\Delta U = Q \, \Delta V$$

The rate at which the system loses electric potential energy as the charge Q passes through the resistor

$$\frac{dU}{dt} = \frac{dQ}{dt} \Delta V = I \, \Delta V$$

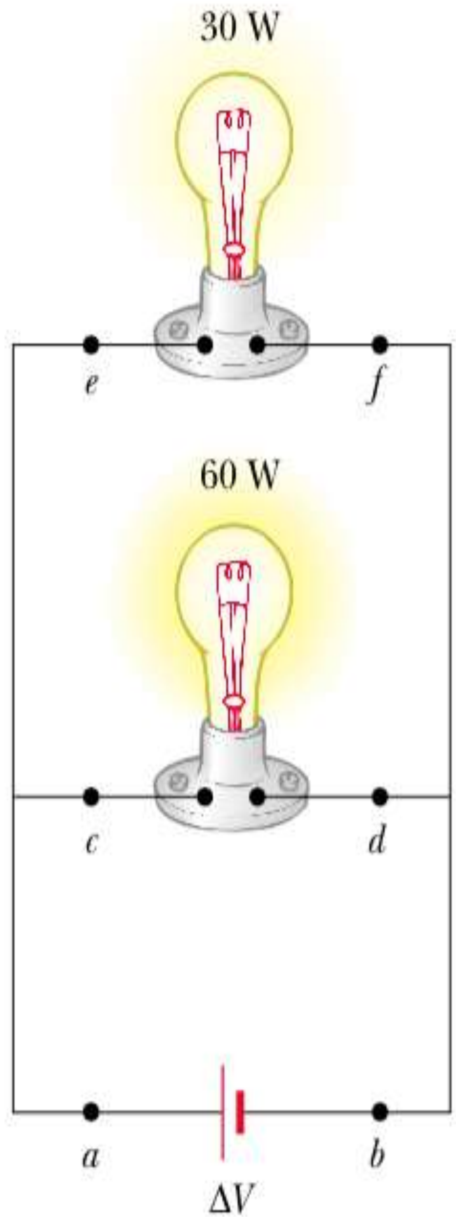
The electric power P is the rate at which energy is delivered to the resistor:

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

The electric power P unit is Watt

Quick Quiz 27.7 The same potential difference is applied to the two lightbulbs shown in Figure 27.14. Which one of the following statements is true? (a) The 30-W bulb carries the greater current and has the higher resistance. (b) The 30-W bulb carries the greater current, but the 60-W bulb has the higher resistance. (c) The 30-W bulb has the higher resistance, but the 60-W bulb carries the greater current. (d) The 60-W bulb carries the greater current and has the higher resistance.

Figure 27.14 (Quick Quiz 27.7) These lightbulbs operate at their rated power only when they are connected to a 120-V source.



Example 27.7 Power in an Electric Heater

An electric heater is constructed by applying a potential difference of 120 V to a Nichrome wire that has a total resistance of 8.00 Ω. Find the current carried by the wire and the power rating of the heater.

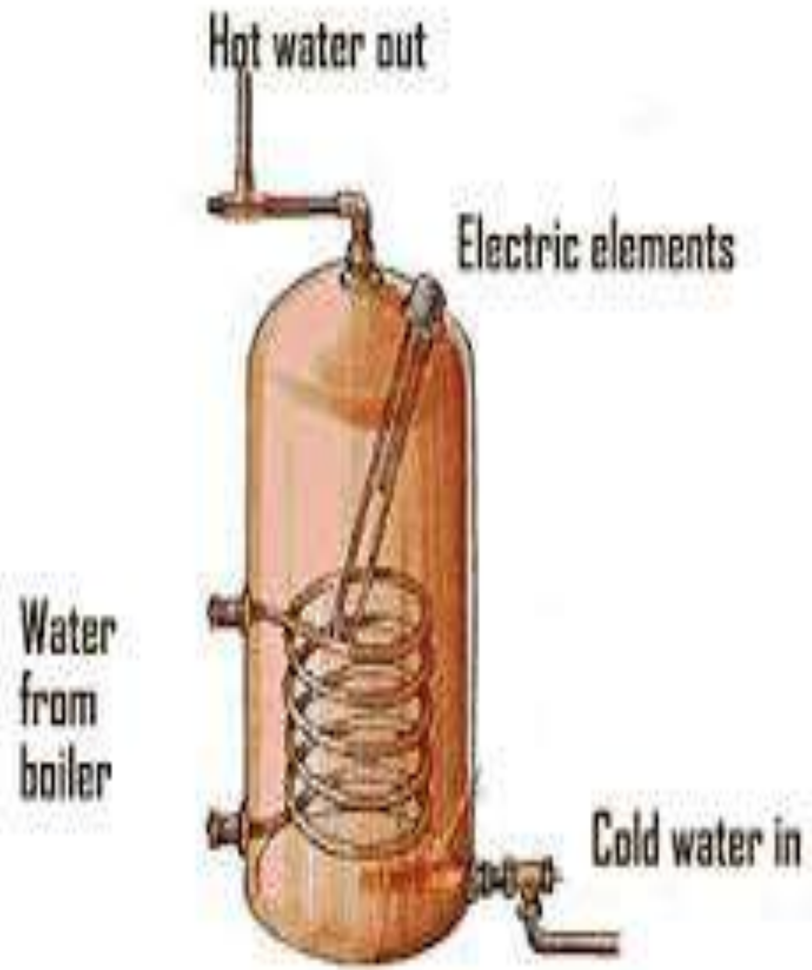
Example 27.8 Linking Electricity and Thermodynamics

(A) What is the required resistance of an immersion heater that will increase the temperature of 1.50 kg of water from 10.0°C to 50.0°C in 10.0 min while operating at 110 V?

(B) Estimate the cost of heating the water.

Assume that the price is 10 cents per kilowatt.hour

c (water) = 4186 J/kg.°C


Hot water out
Electric elements
Water
from
boiler
Cold water in

Useful Equations:

If we have a material with mass m, and we want to increase its temperature by ΔT, then we need to transfer energy to this material call it Q (not charge – be careful!) This heat energy is given by (c is a constant called specific heat):

$$Q = mc\,\Delta T$$

We always express the power as:

$$Power = \frac{Energy}{time}$$