Chapter 25

Current, Resistance, and Electromotive Force

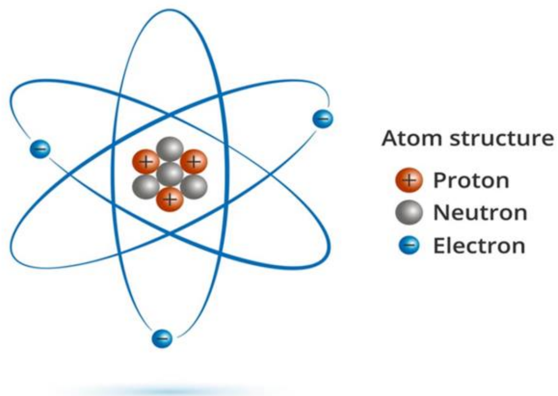
Goals for Chapter 25

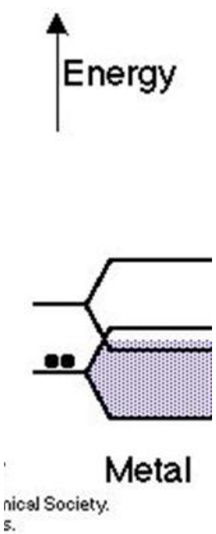
- To understand current and how charges move in a conductor
- To understand resistivity and conductivity
- To calculate the resistance of a conductor
- To learn how an emf causes current in a circuit
- To calculate energy and power in circuits

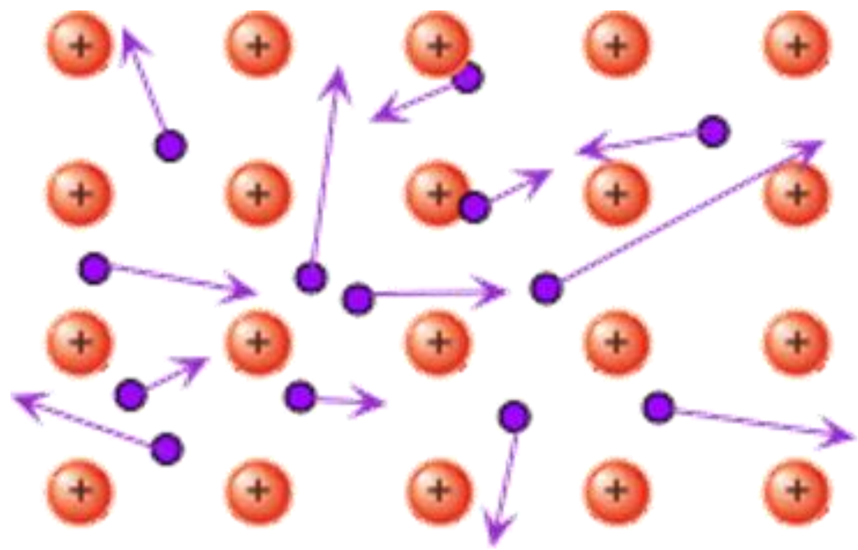
Introduction

- Electric currents flow through light bulbs.
- Electric circuits contain charges in motion.
- Circuits are at the heart of modern devices such as computers, televisions, and industrial power systems.

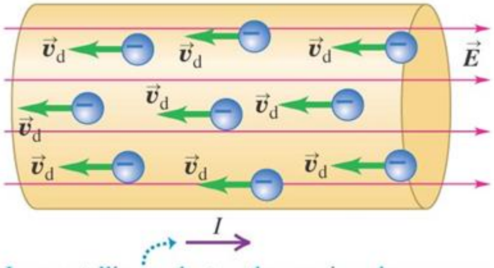
Electrons in Metal





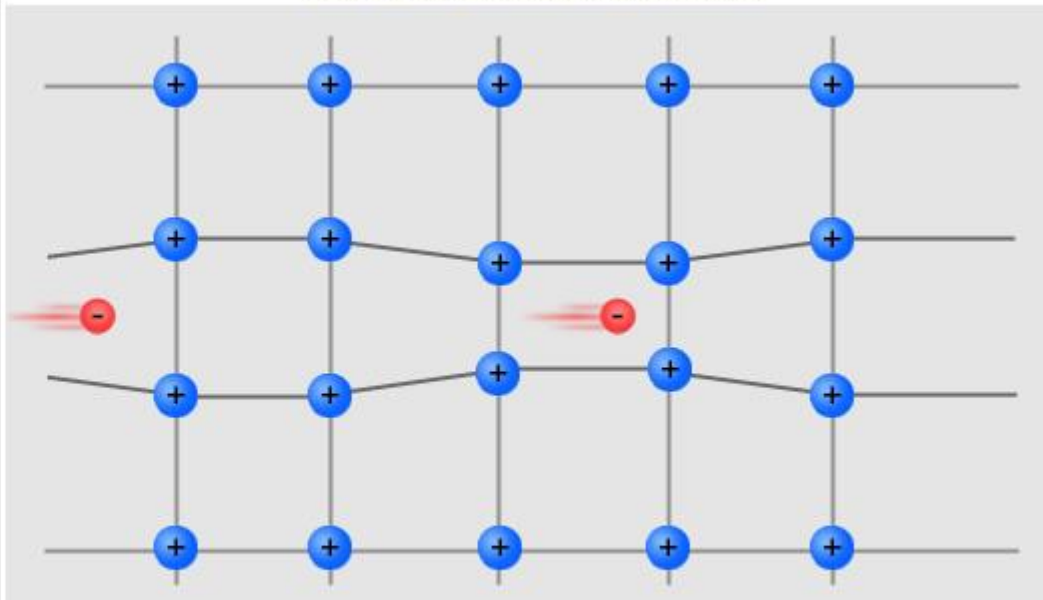


Current


$\vec{v}_d$
$\vec{E}$
I
In a metallic conductor, the moving charges are electrons — but the *current* still points in the direction positive charges would flow.

Superconducting Current

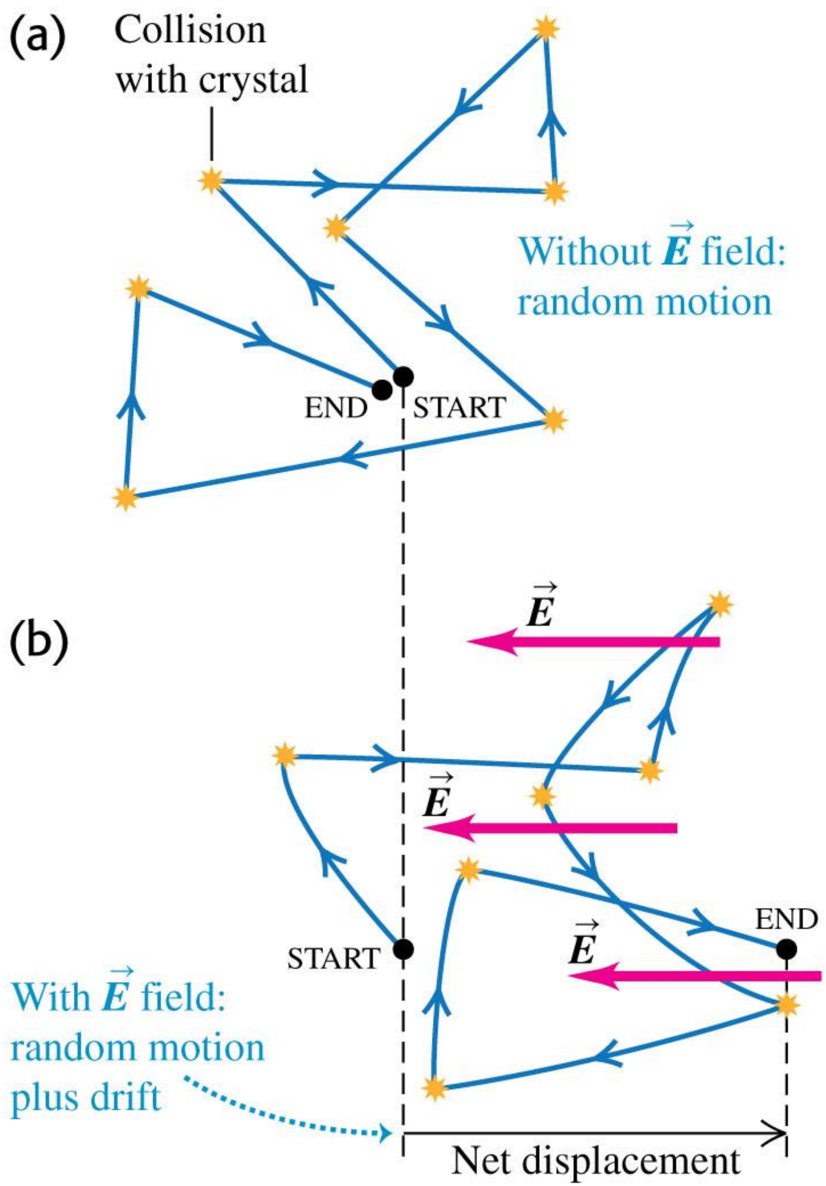
Cooper pairs make super conductors

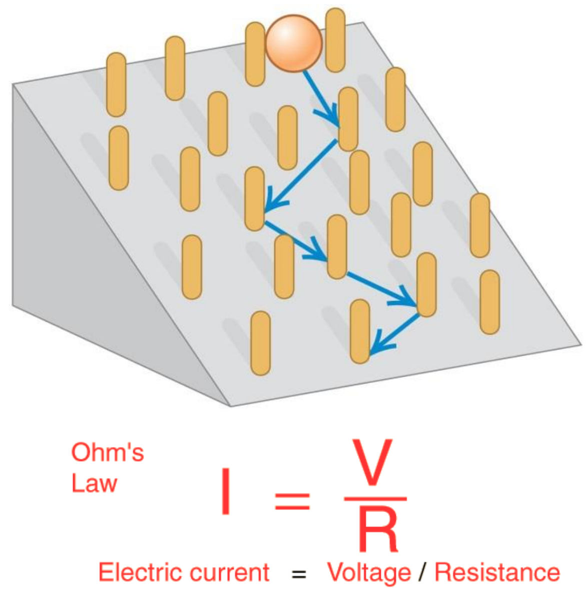


At extremely low temperatures, an electron can draw the positive ions in a superconducting material towards it. This movement of the ions creates a more positive region that attracts another electron to the area.

Theory of metallic conduction

- Follow the discussion in the text using Figures 25.26 (right) and 25.27 (below). Both illustrate the random motion of electrons in a conductor.
- Follow Example 25.11.

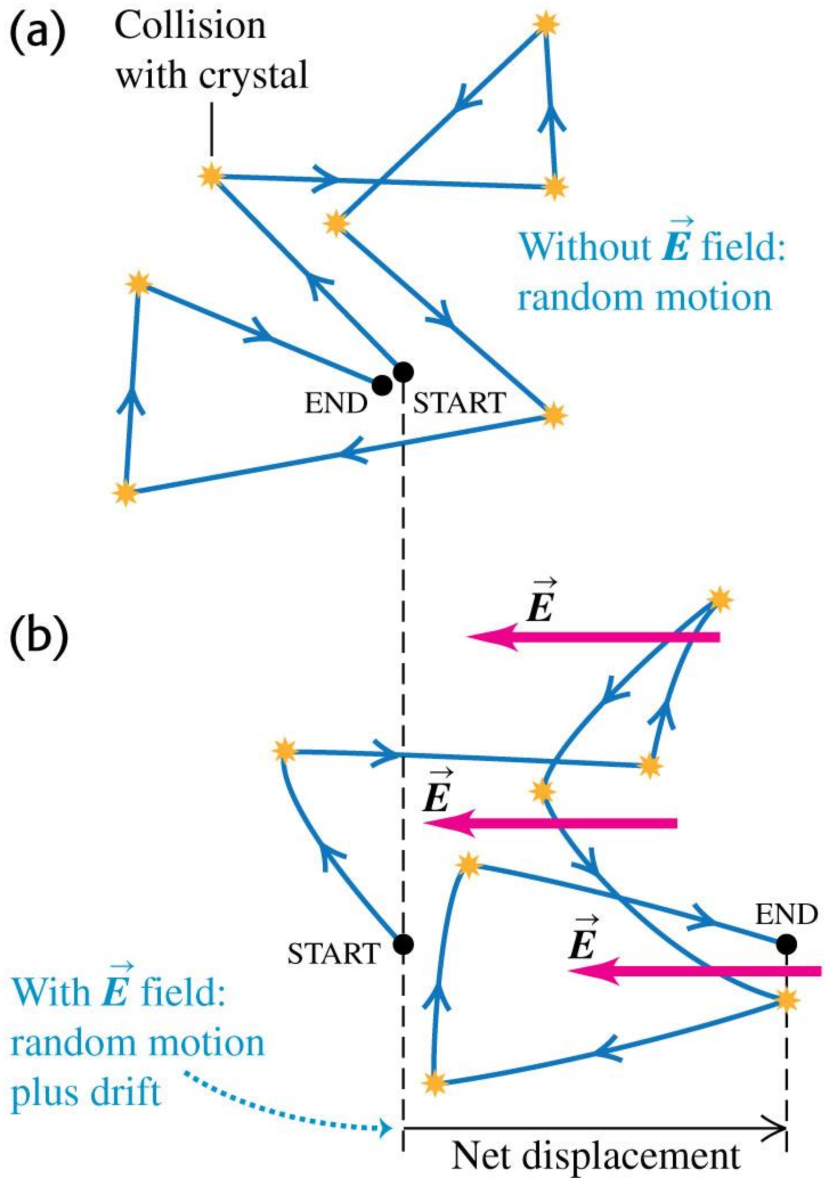




Theory of metallic conduction

10^6 m/s, *V.S.* 10^{-4} m/s.

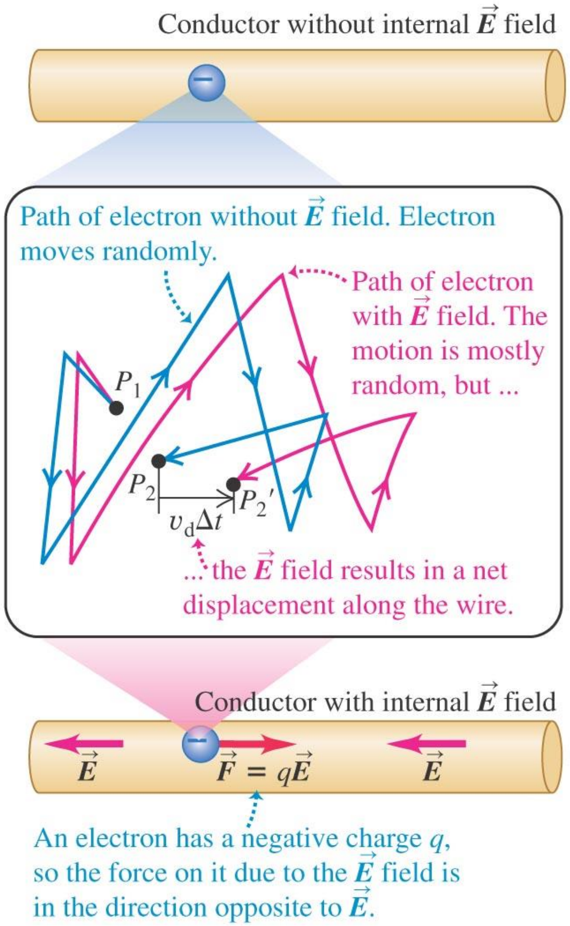
: **mean free time,** denoted by τ.



Current

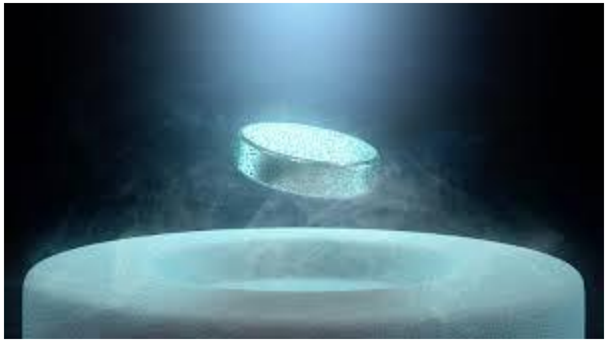
- A *current* is any motion of charge from one region to another. Current is defined as $I = dQ/dt$.
- An electric field in a conductor causes charges to flow. (See Figure 25.1 at the right.)

E≠ 0 anymore

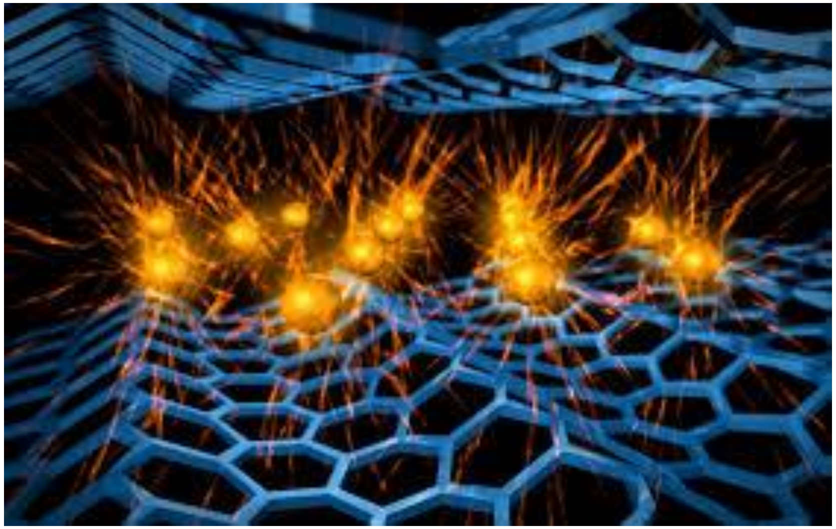


the **drift velocity** $\vec{v}_d$ of the particles.

Theory of metallic conduction

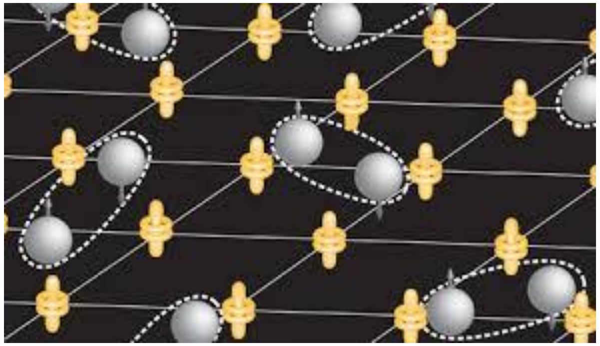


Superconductor



scattering

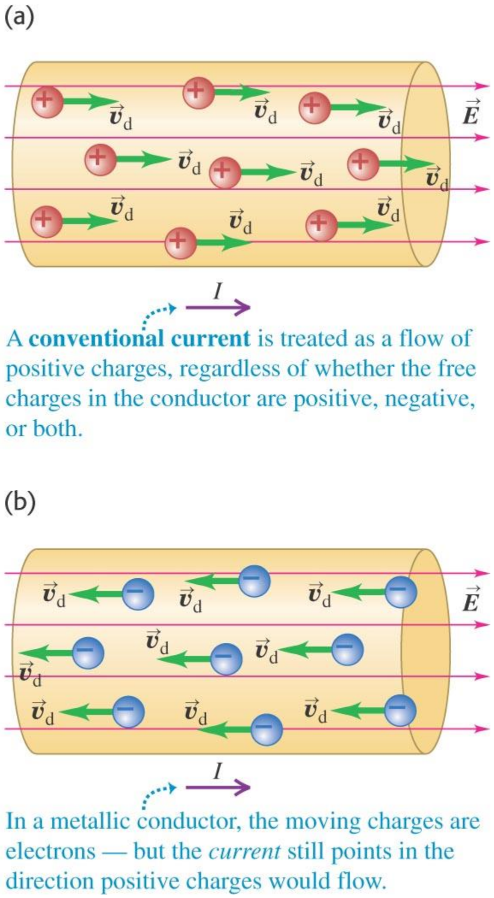
mean free time, denoted by τ.



Cooper pairs

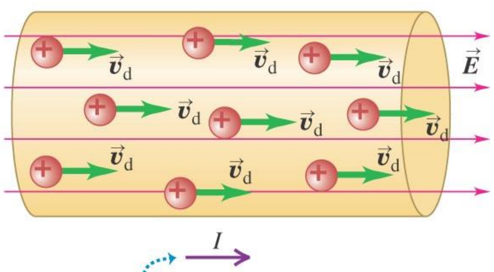
Direction of current flow

- A current can be produced by positive or negative charge flow.
- *Conventional current* is treated as a flow of positive charges.
- The moving charges in metals are electrons (see figure below).



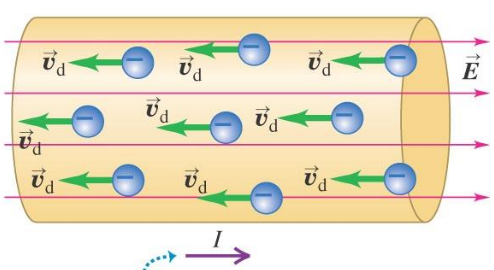
Direction of current flow

(a)



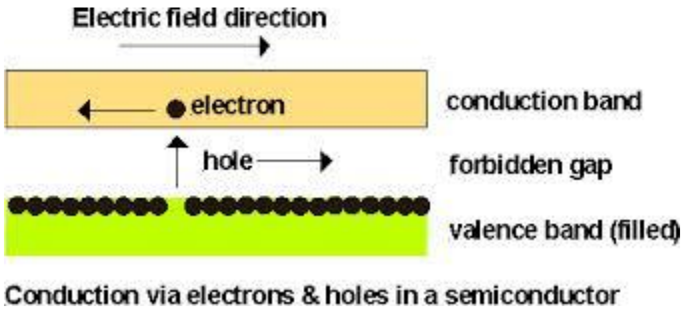
A **conventional current** is treated as a flow of positive charges, regardless of whether the free charges in the conductor are positive, negative, or both.

(b)



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

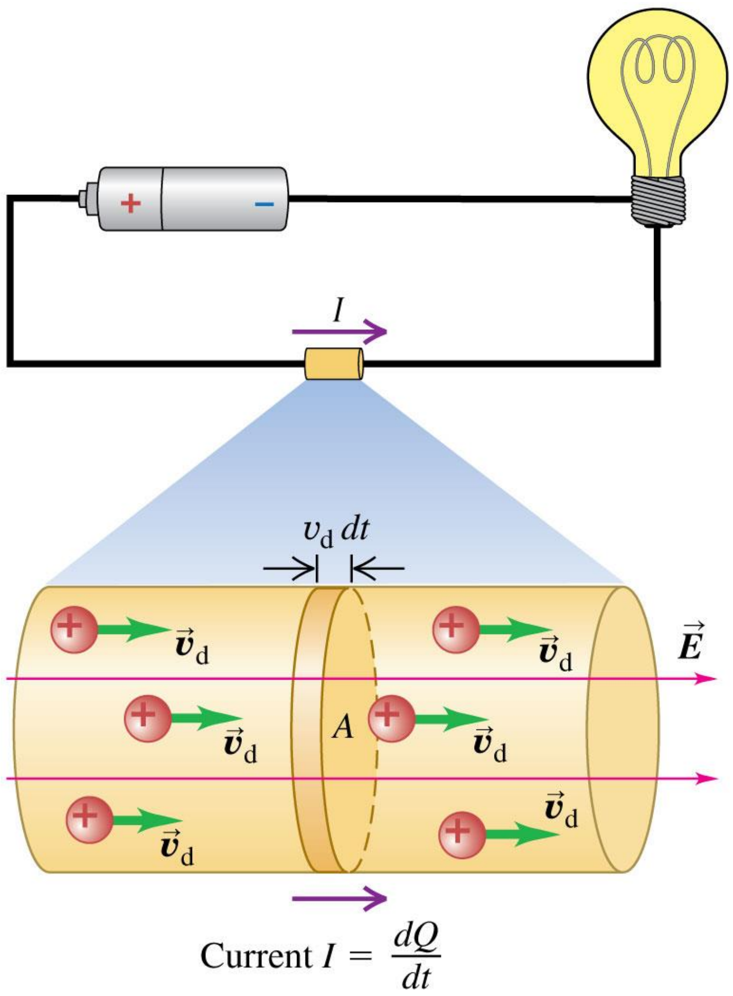
Plasma



Semiconductor

Current, drift velocity, and current density

- Follow the discussion of current, drift velocity, and current density.
- Figure 25.3 at the right shows the positive charges moving in the direction of the electric field.
- Follow Example 25.1.



Current, drift velocity, and current density

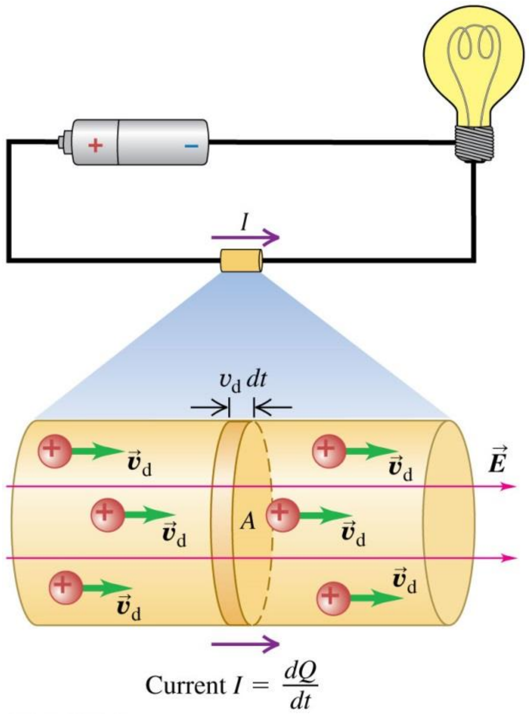
$$dQ = q(nAv_d\,dt) = nqv_dA\,dt$$

and the current is

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

The current *per unit cross-sectional area* is called the **current density** J:

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



Resistivity

$$\vec{a} = \frac{\vec{F}}{m} = \frac{q\vec{E}}{m}$$

$$\vec{v} = \vec{v}_0 + \vec{a}\tau$$

$$\vec{v}_d = \frac{q\tau}{m}\vec{E}$$

the drift velocity $\vec{v}_d$:

$$\vec{v}_{av} = \vec{a}\tau = \frac{q\tau}{m}\vec{E}$$

mean free time, denoted by τ.

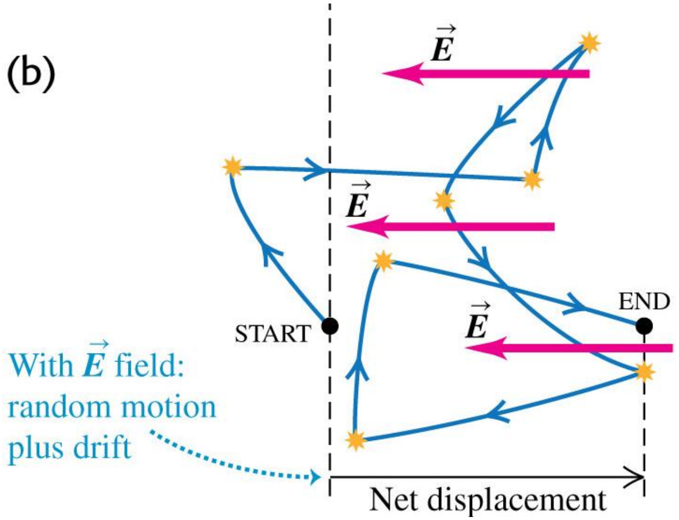
, the initial velocity $\vec{v}_0$ is zero

- The *resistivity* of a material is the ratio of the electric field in the material to the current density it causes:

$$\rho = \frac{E}{J} \qquad \text{(definition of resistivity)}$$

$$\vec{J} = nq\vec{v}_d = \frac{nq^2\tau}{m}\vec{E}$$

$$\rho = \frac{m}{ne^2\tau}$$



Resistivity

- The *resistivity* of a material is the ratio of the electric field in the material to the current density it causes:

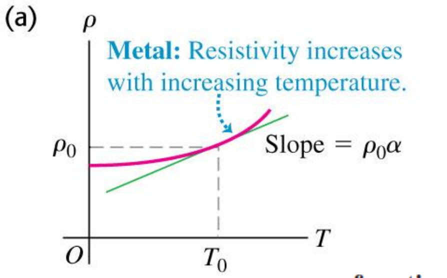
$$\rho = \frac{E}{J} \qquad \text{(definition of resistivity)}$$

- The *conductivity* is the reciprocal of the resistivity.

Table 25.1 Resistivities at Room Temperature (20 °C)

Substance		$\rho\ (\Omega \cdot \mathrm{m})$	Substance	$\rho\ (\Omega \cdot \mathrm{m})$
Conductors			**Semiconductors**	
Metals	Silver	1.47×10^{-8}	Pure carbon (graphite)	3.5×10^{-5}
	Copper	1.72×10^{-8}	Pure germanium	0.60
	Gold	2.44×10^{-8}	Pure silicon	2300
	Aluminum	2.75×10^{-8}	**Insulators**	
	Tungsten	5.25×10^{-8}	Amber	5×10^{14}
	Steel	20×10^{-8}	Glass	10^{10}–10^{14}
	Lead	22×10^{-8}	Lucite	$>10^{13}$
	Mercury	95×10^{-8}	Mica	10^{11}–10^{15}
Alloys	Manganin (Cu 84%, Mn 12%, Ni 4%)	44×10^{-8}	Quartz (fused)	75×10^{16}
	Constantan (Cu 60%, Ni 40%)	49×10^{-8}	Sulfur	10^{15}
	Nichrome	100×10^{-8}	Teflon	$>10^{13}$
			Wood	10^{8}–10^{11}

Resistivity and temperature



$$\rho(T) = \rho_0[1 + \alpha(T - T_0)] \quad \text{(temperature dependence of resistivity)}$$

$$\rho = \frac{m}{ne^2\tau}$$

mean free time, denoted by τ.

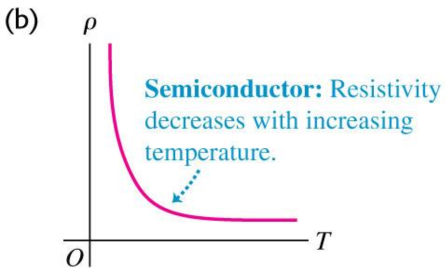
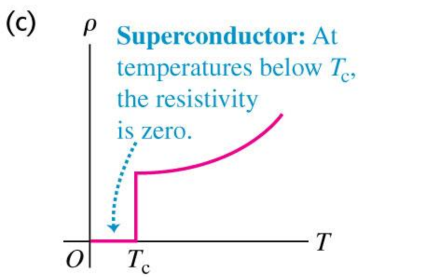
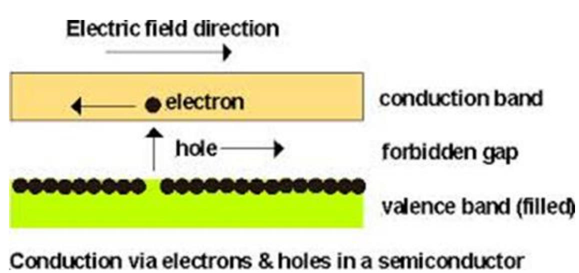


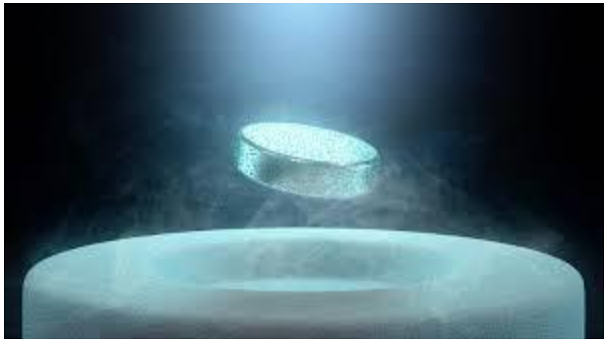
Table 25.2 Temperature Coefficients of Resistivity (Approximate Values Near Room Temperature)

Material	$\alpha\,[(^\circ\mathrm{C})^{-1}]$	Material	$\alpha\,[(^\circ\mathrm{C})^{-1}]$
Aluminum	0.0039	Lead	0.0043
Brass	0.0020	Manganin	0.00000
Carbon (graphite)	−0.0005	Mercury	0.00088
Constantan	0.00001	Nichrome	0.0004
Copper	0.00393	Silver	0.0038
Iron	0.0050	Tungsten	0.0045

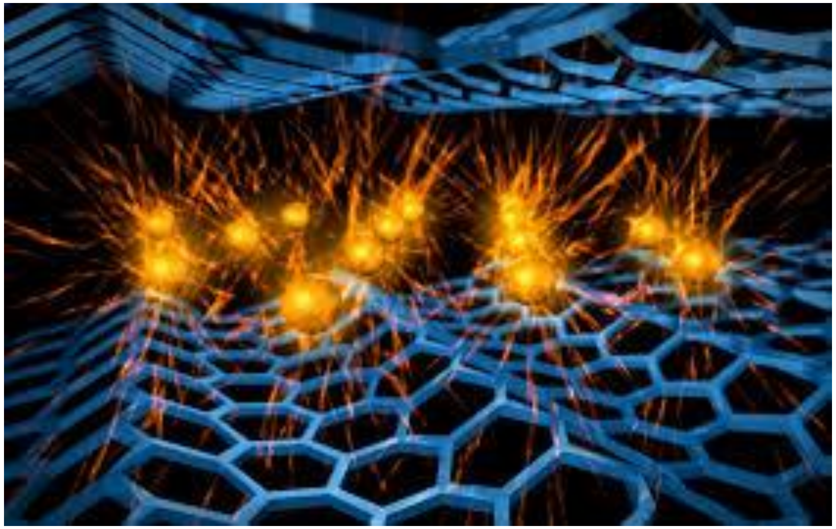




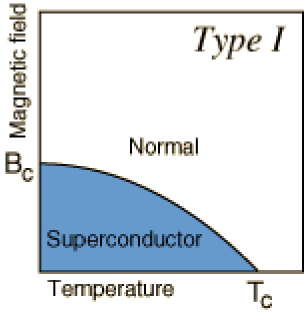
Theory of metallic conduction

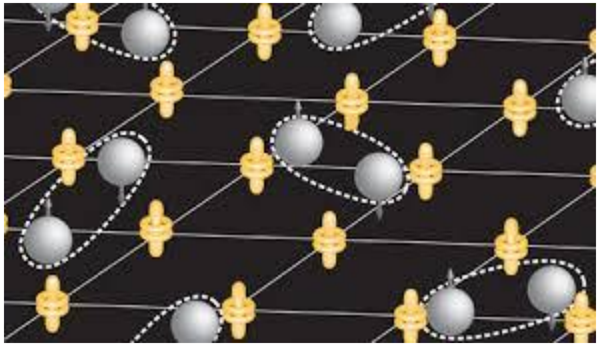


Superconductor



scattering

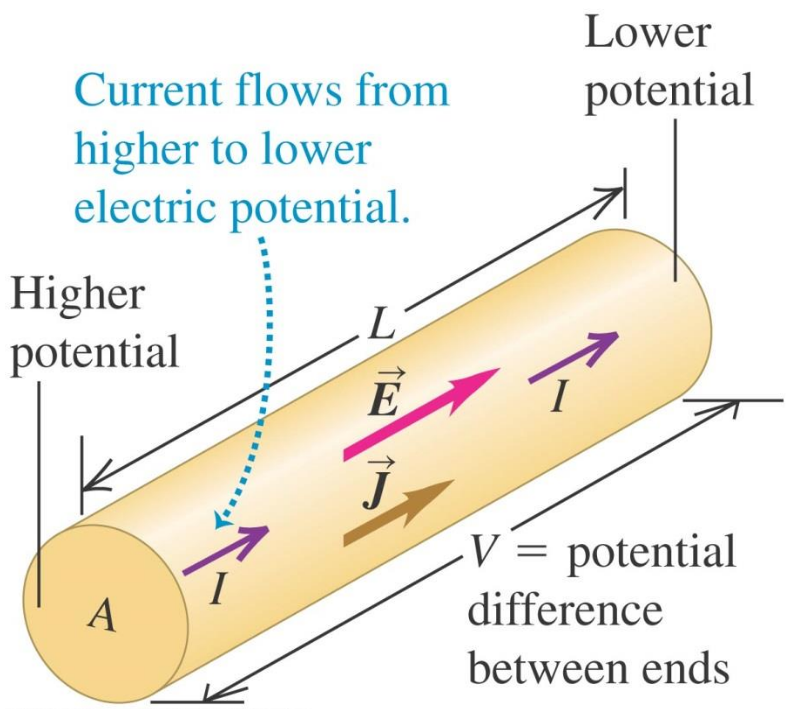




Cooper pairs

Resistance (Material + Geo.)

- The *resistance* of a conductor is $\underline{R = \rho L/A}$ (see Figure 25.7 below).
- The potential across a conductor is $\underline{V = IR}$.
- If V is directly proportional to I (that is, if R is constant), the equation $\underline{V = IR}$ is called <u>*Ohm's law*</u>.

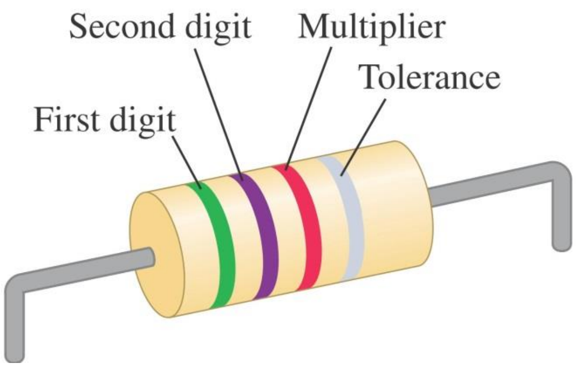


Resistors are color-coded for easy identification

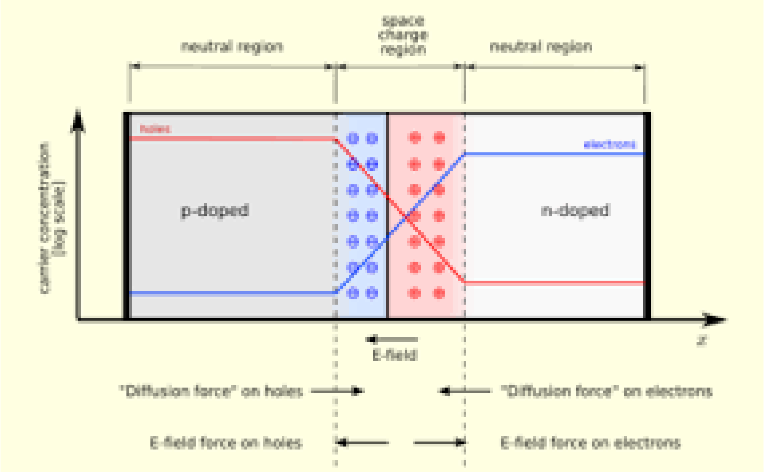
- This resistor has a resistance of 5.7 kΩ with a tolerance of ±10%.

Table 25.3 Color Codes for Resistors

Color	Value as Digit	Value as Multiplier
Black	0	1
Brown	1	10
Red	2	10^2
Orange	3	10^3
Yellow	4	10^4
Green	5	10^5
Blue	6	10^6
Violet	7	10^7
Gray	8	10^8
White	9	10^9

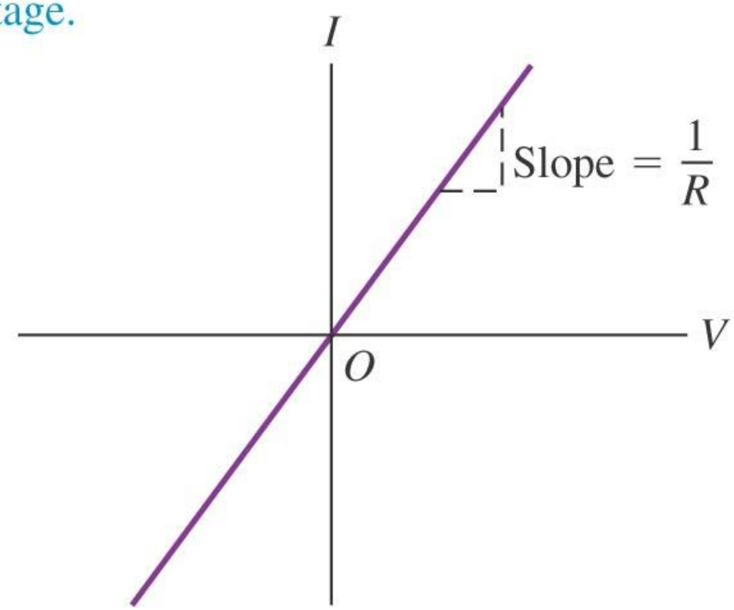


Ohmic and nonohmic resistors

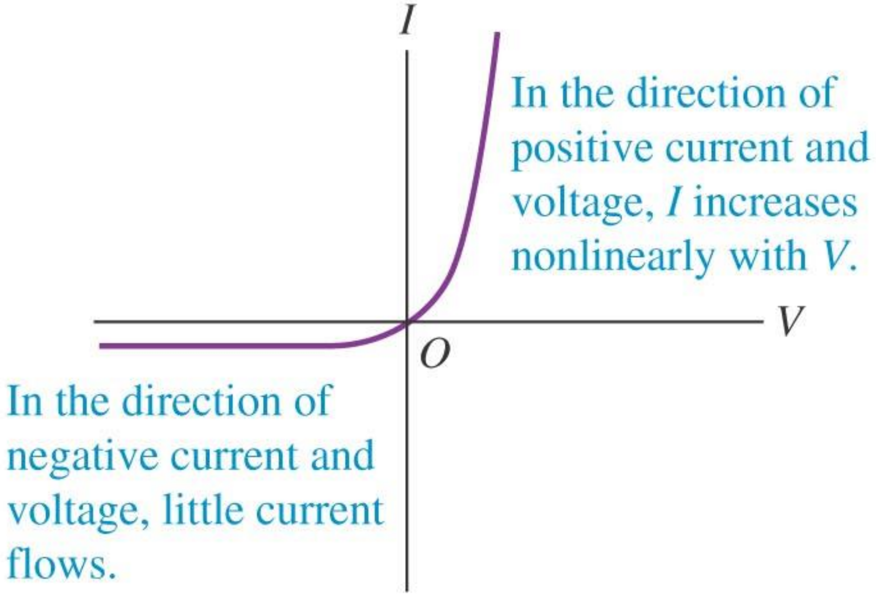


(a)

Ohmic resistor (e.g., typical metal wire): At a given temperature, current is proportional to voltage.



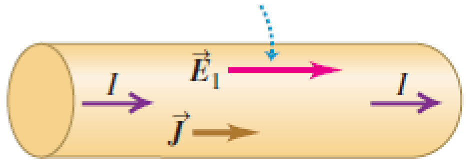
Semiconductor diode: a nonohmic resistor



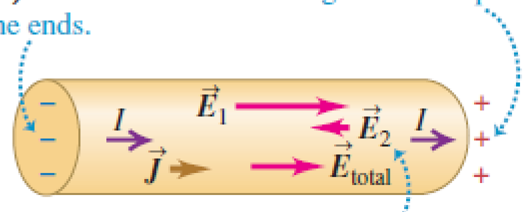
Electromotive force and circuits

For a conductor to have a steady current, it must be part of a path that forms a closed loop or **complete circuit.** Here's why. If you establish an electric field $\vec{E}_1$

(a) An electric field $\vec{E}_1$ produced inside an isolated conductor causes a current.

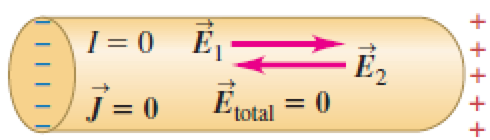


(b) The current causes charge to build up at the ends.



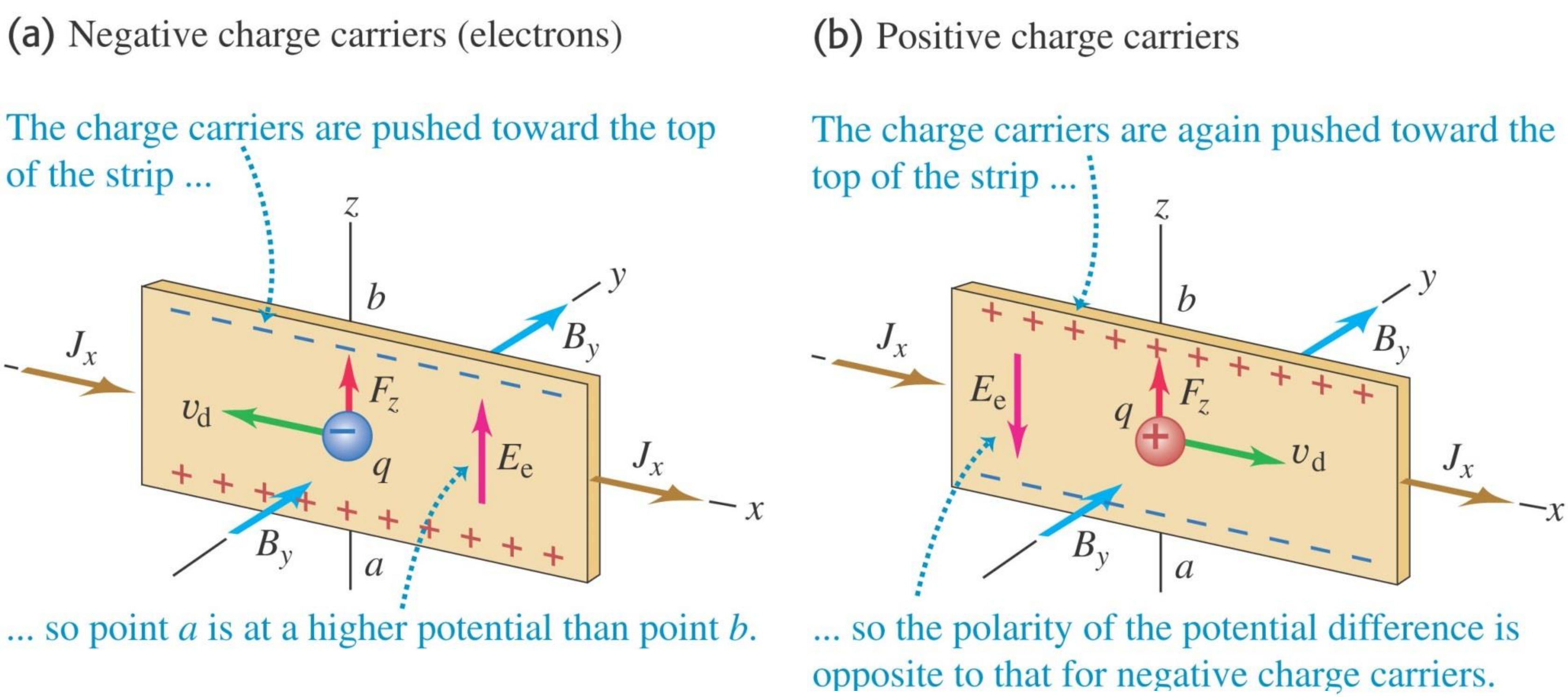
The charge buildup produces an opposing field $\vec{E}_2$, thus reducing the current.

(c) After a very short time $\vec{E}_2$ has the same magnitude as $\vec{E}_1$; then the total field is $\vec{E}_{total} = 0$ and the current stops completely.



The Hall Effect

- Follow the discussion of the Hall effect in the text using Figure 27.41 below.
- Follow Example 27.12.



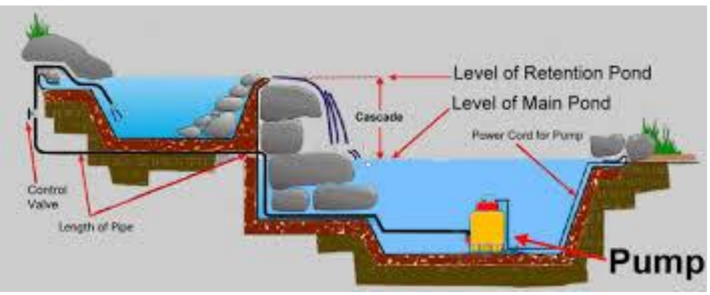
$$qE_z + qv_\mathrm{d}B_y = 0$$

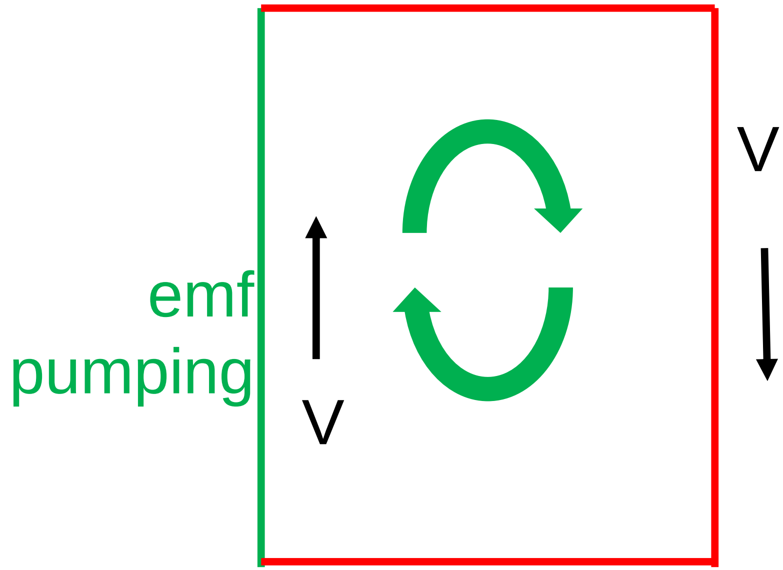
$$J_x = nqv_\mathrm{d}$$

$$nq = \frac{-J_xB_y}{E_z} \qquad \text{(Hall effect)}$$

Electromotive force and circuits

For a conductor to have a steady current, it must be part of a path that forms a closed loop or **complete circuit.** Here's why. If you establish an electric field $\vec{E}_1$





Ohm's Law

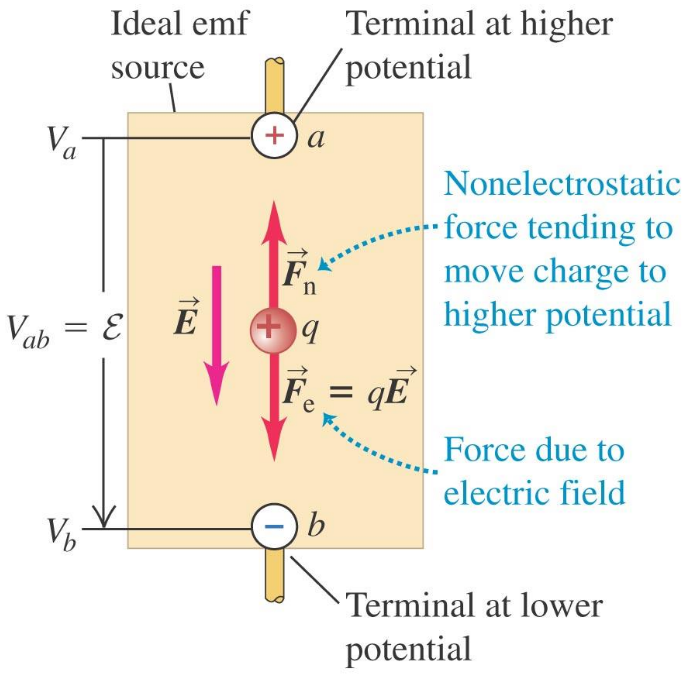
$$I = \frac{V}{R}$$

Electric current = Voltage / Resistance

Electromotive force and circuits

- An *electromotive force* (*emf*) makes current flow. In spite of the name, an emf is *not* a force.

- The figures below show a source of emf in an open circuit (left) and in a complete circuit (right).



When the emf source is not part of a closed circuit, $F_n = F_e$ and there is no net motion of charge between the terminals.

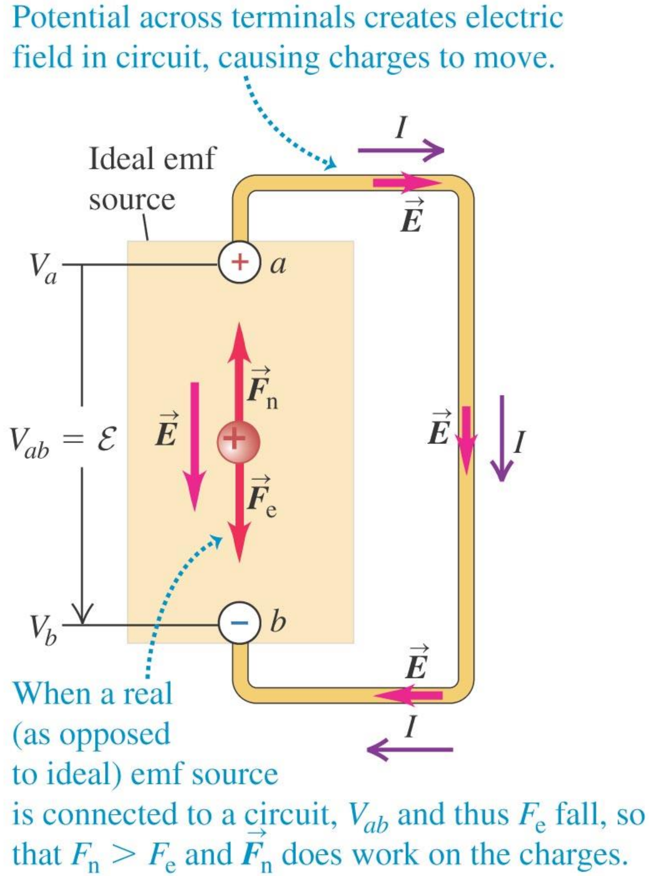
$W_n = q\mathcal{E}$ $\qquad$ qV_{ab},

$$q\mathcal{E} = qV_{ab},$$

$$V_{ab} = \mathcal{E} \qquad \text{(ideal source of emf)}$$

Electromotive force and circuits

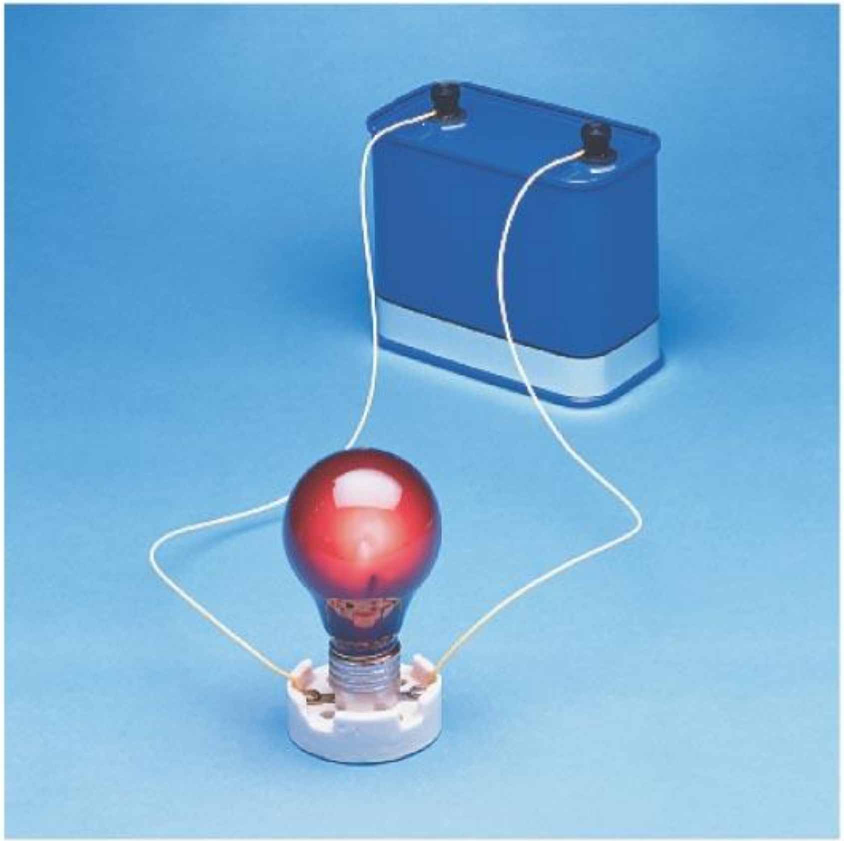
- An *electromotive force* (*emf*) makes current flow. In spite of the name, an emf is *not* a force.
- The figures below show a source of emf in an open circuit (left) and in a complete circuit (right).



$$\boxed{\mathcal{E} = V_{ab} = IR \qquad \text{(ideal source of emf)}}$$

Internal resistance

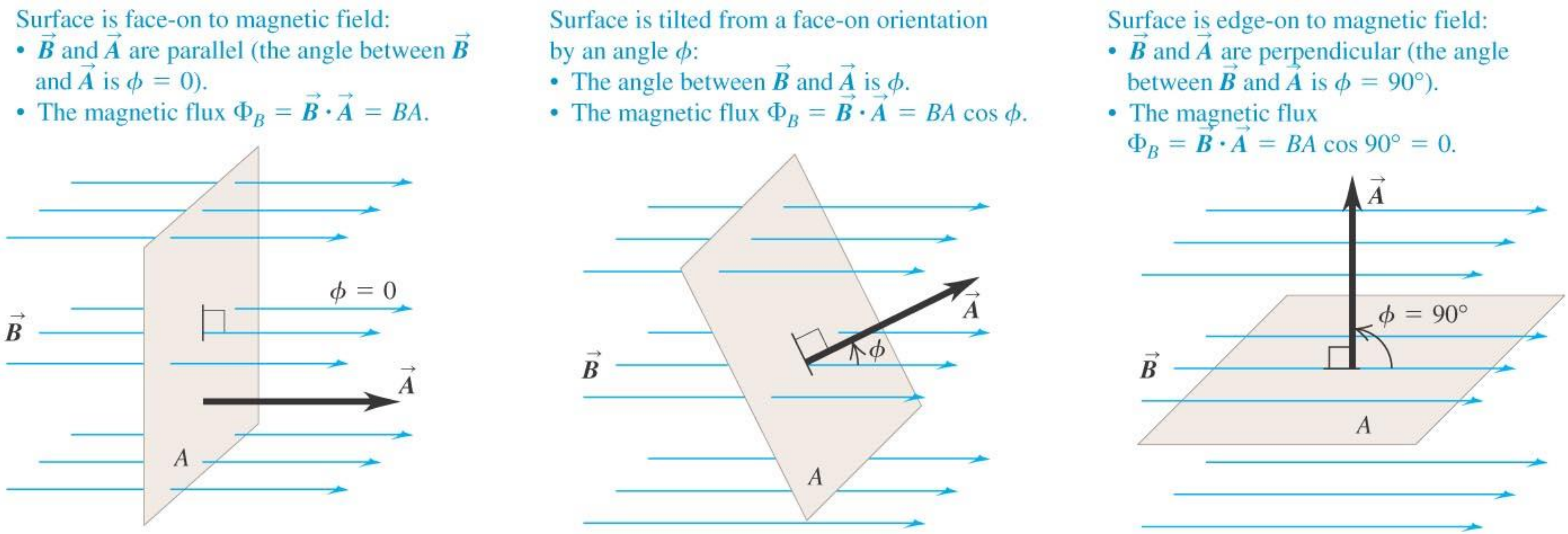
- Real sources of emf actually contain some *internal resistance r*.
- The *terminal voltage* of an emf source is $V_{ab} = \xi - Ir$.
- The terminal voltage of the 12-V battery shown at the right is less than 12 V when it is connected to the light bulb.

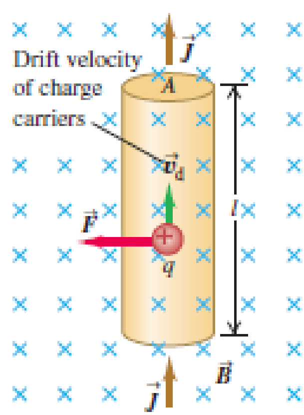


$$V_{ab} = \mathcal{E} - Ir \qquad \text{(terminal voltage, source with internal resistance)}$$

Faraday's law

- The flux depends on the orientation of the surface with respect to the magnetic field. See Figure 29.4 below.

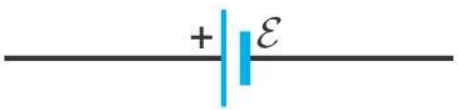
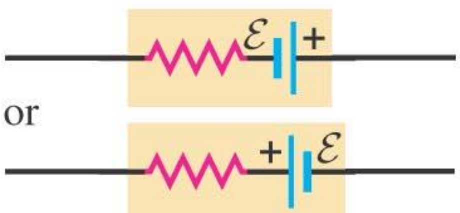
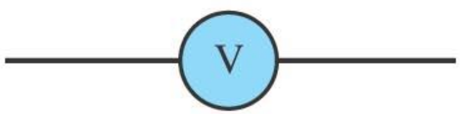
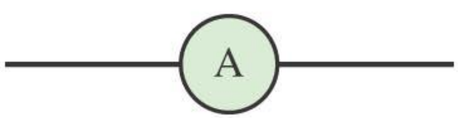




Symbols for circuit diagrams

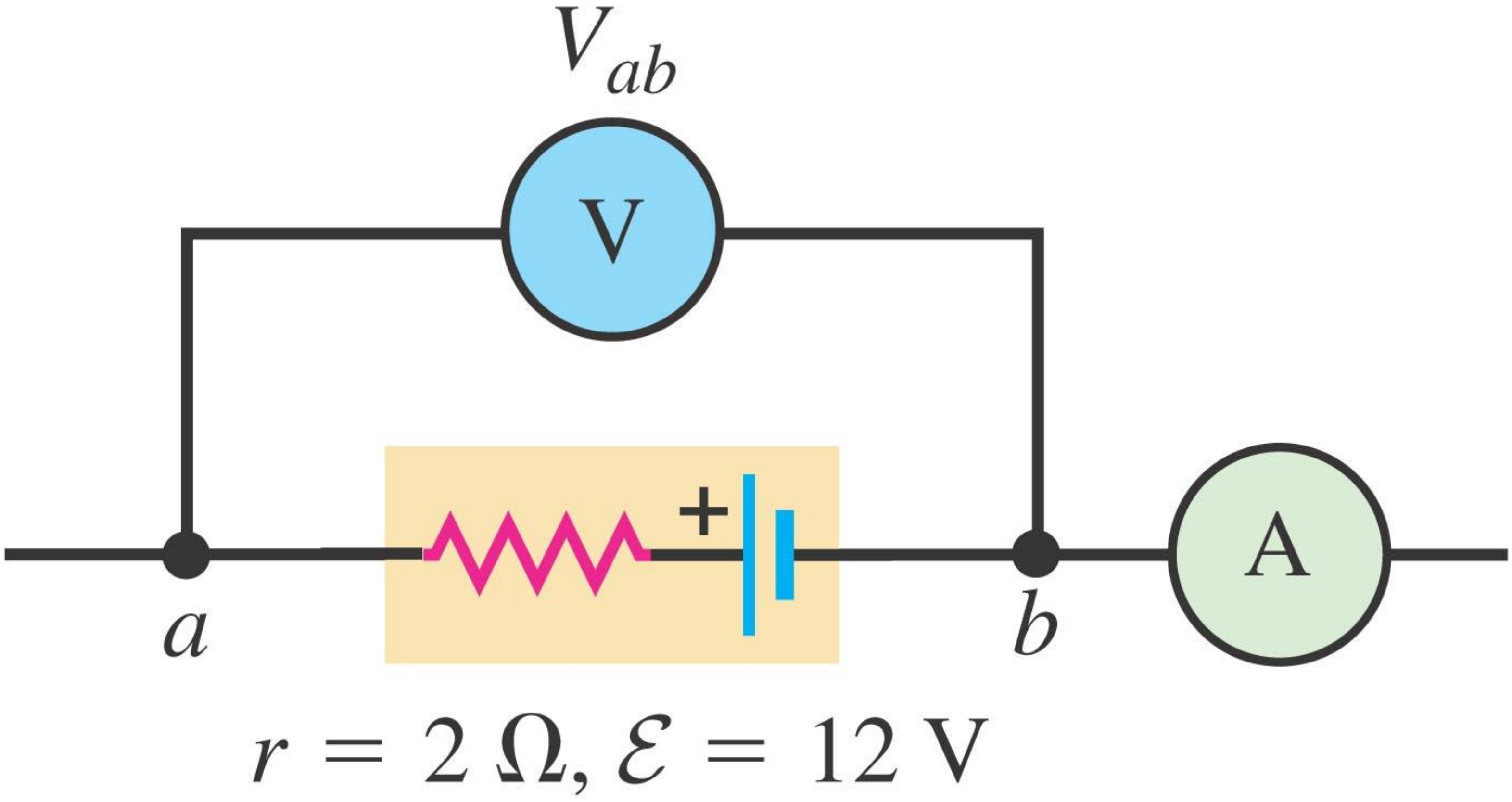
- Table 25.4 shows the usual symbols used in circuit diagrams.

Table 25.4 Symbols for Circuit Diagrams

	Conductor with negligible resistance
	Resistor
	Source of emf (longer vertical line always represents the positive terminal, usually the terminal with higher potential)
	Source of emf with internal resistance r (r can be placed on either side)
	Voltmeter (measures potential difference between its terminals)
	Ammeter (measures current through it)

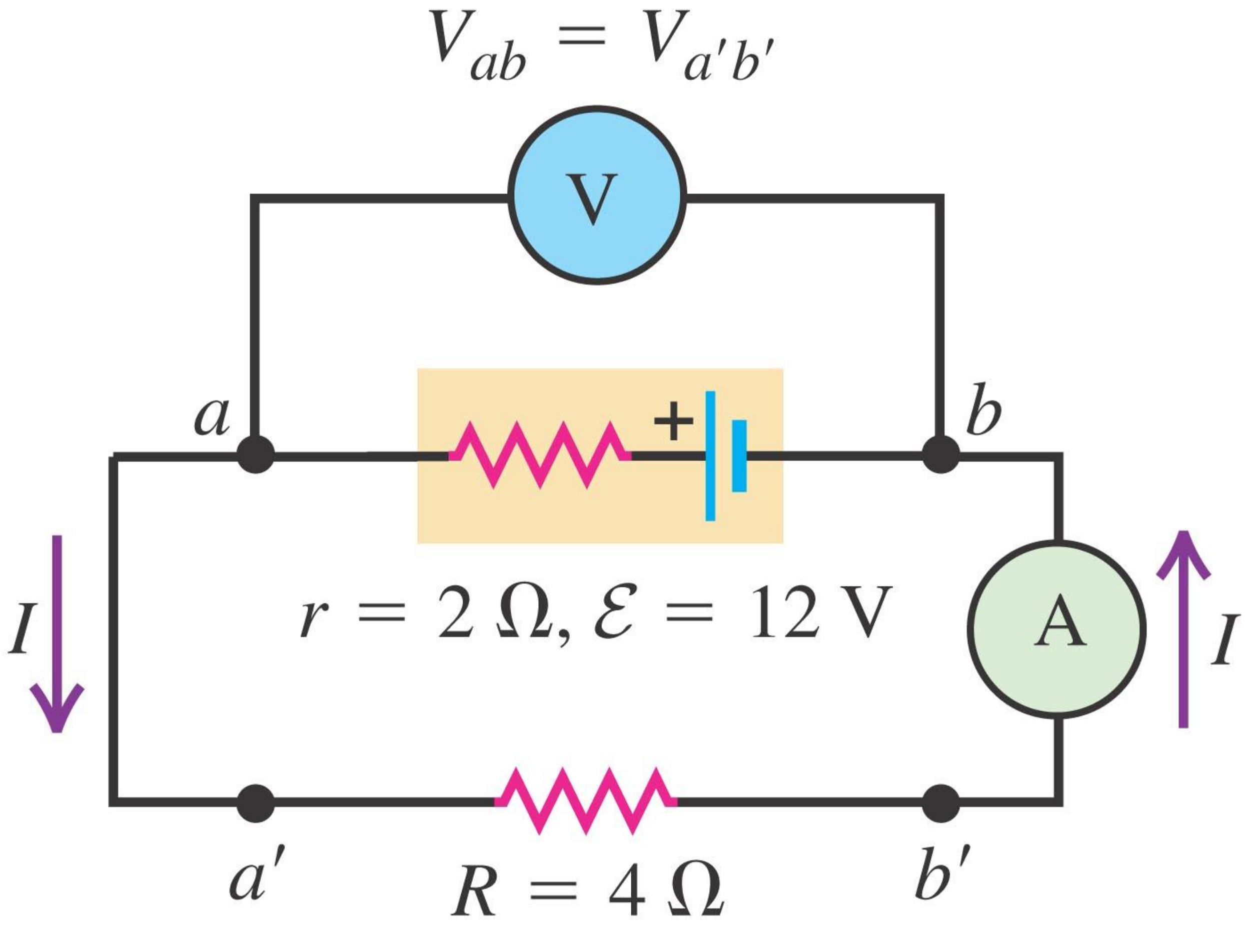
A source in an open circuit

- Follow Conceptual Example 25.4 using Figure 25.16 below.



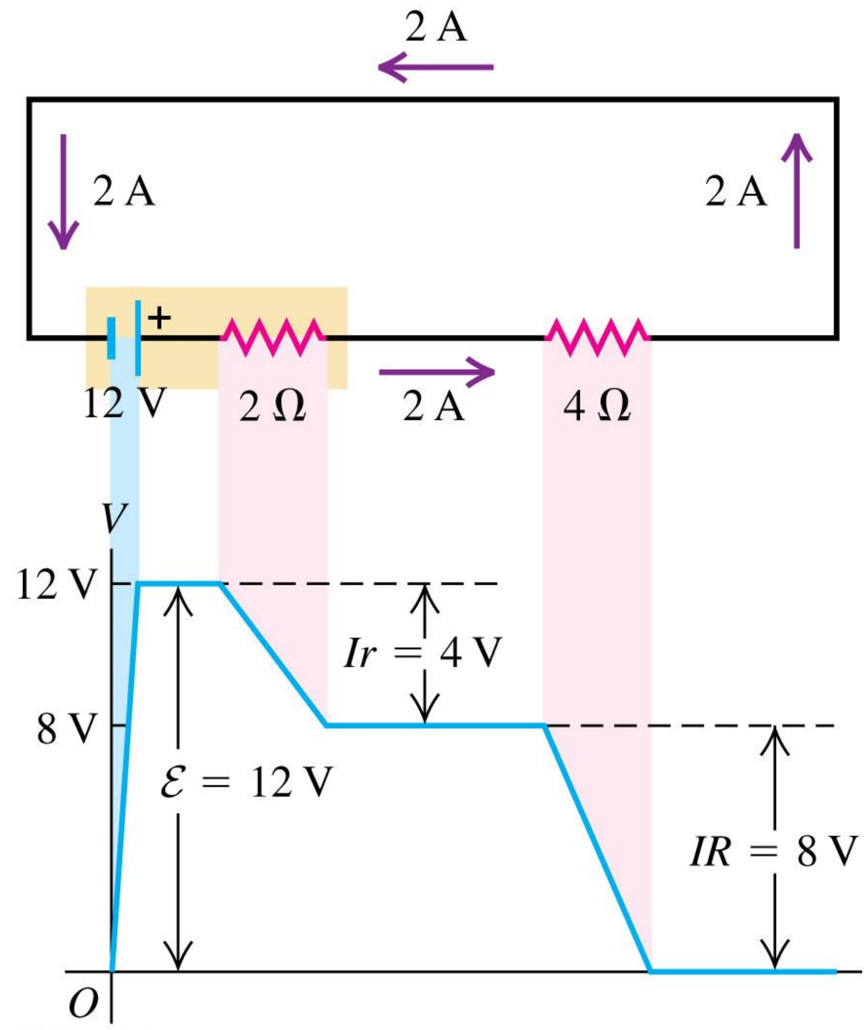
Source in a complete circuit

- Follow Example 25.5 using Figure 25.17 below.



Potential changes around a circuit

- The net change in potential must be zero for a round trip in a circuit.
- Follow Figure 25.20 at the right.



Energy and power in electric circuits

- The rate at which energy is delivered to (or extracted from) a circuit element is $P = V_{ab}I$. See Figures 25.21 (below) and 25.22 (at right).
- The power delivered to a pure resistor is $P = I^2R = V_{ab}^2/R$.