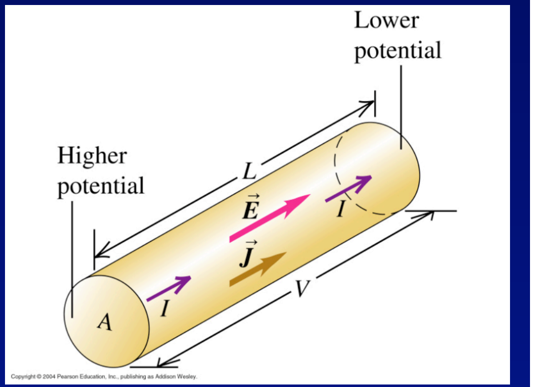
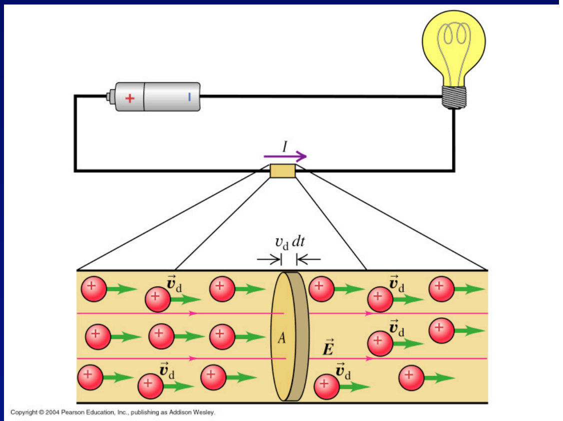
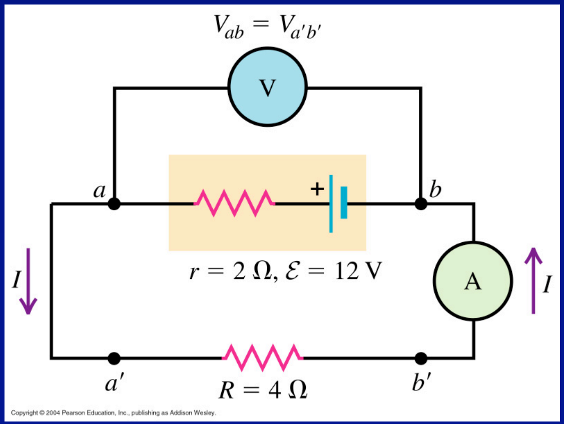
Chapter 25

Currents, Resistance, and Electromotive Force

- Electric current
- Resistance and Resistivity
  - *Ohm's Law*
- Electric motive force
  - Battery
  - Simple circuits
  - Energy and power in circuits







Electric Current

New Topic

Electric Current

- The presence of electric field leads to a force on a free charge:

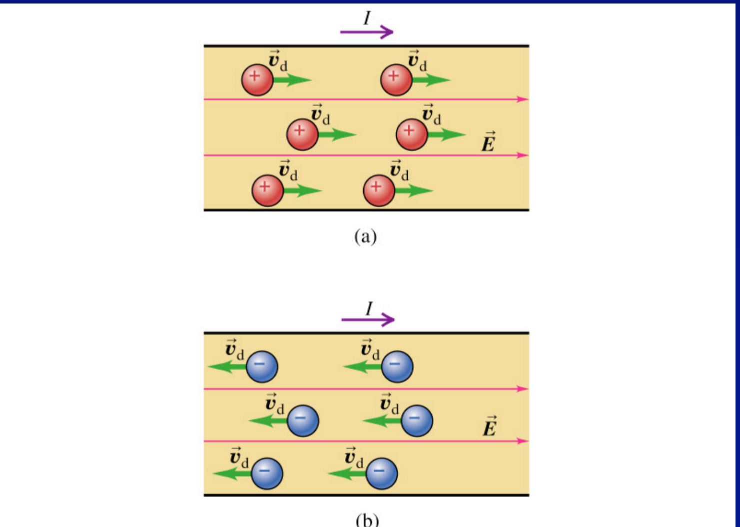
$$\vec{F} = q\vec{E}$$

- The motion of charges leads to an ***electric current:***

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

- **SI unit: *Coulomb/second = Ampere***
- ***1 A = 1 C/s***

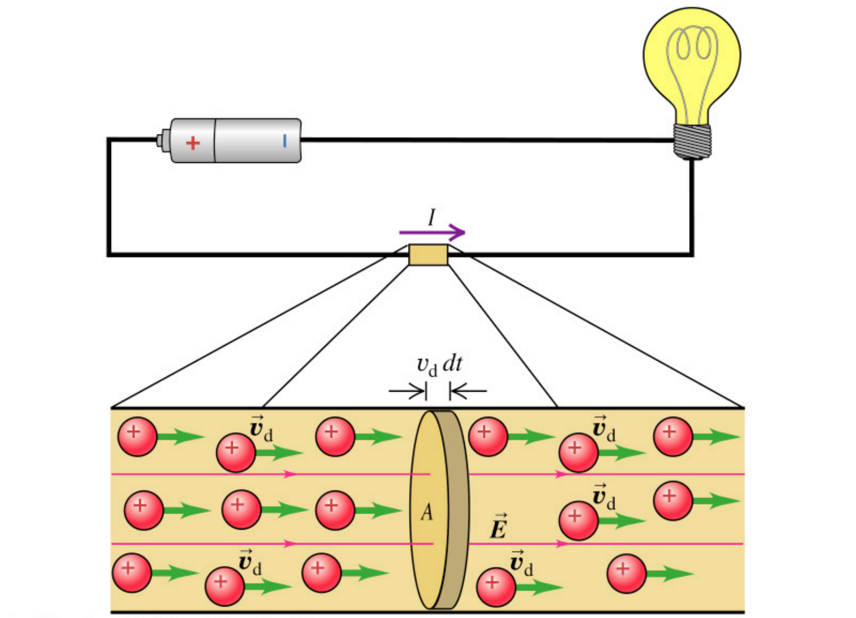
- **The same current can be produced by motion of *positive charge* or *negative charge.***



Current: microscopic view

Current can be related to the drift velocity of moving charges:

$$I = \frac{dQ}{dt} = n\,|\,q\,|\,v_d A$$



n is the number of free charges per unit volume.

Define current density:

$$J = \frac{I}{A} = n\,|\,q\,|\,v_d$$

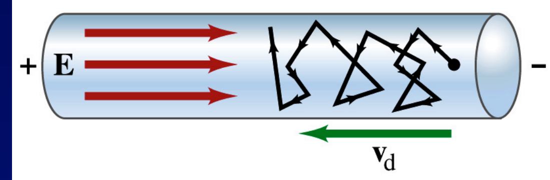
Or in vector form

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

Example 25.1: how fast is the electron drifting ?

- An 18-gauge copper wire of 1.02 mm in diameter carries a current of 1.67 A. Determine
  - Current density in the wire
  - Drift velocity of free electrons

(Assume that one electron per Cu atom is free to move.)



a) $A = \pi r^2 = 8.17 \times 10^{-7}\ \text{m}^2$

$J = I / A = 1.67/8.17 \times 10^{-7} = 2.04 \times 10^6\ \text{A/m}^2$

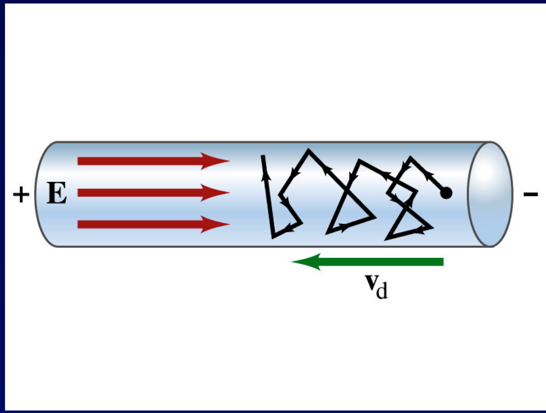
b) The mass of one Cu atom is 63.5 u. The mass density of Cu is $8.9 \times 10^3\ \text{kg/m}^3$. So the number density of electrons is

$$n = \frac{8.9\times10^{3}}{63.5\times1.6605\times10^{-27}} = 8.4\times10^{28}/\text{m}^3$$

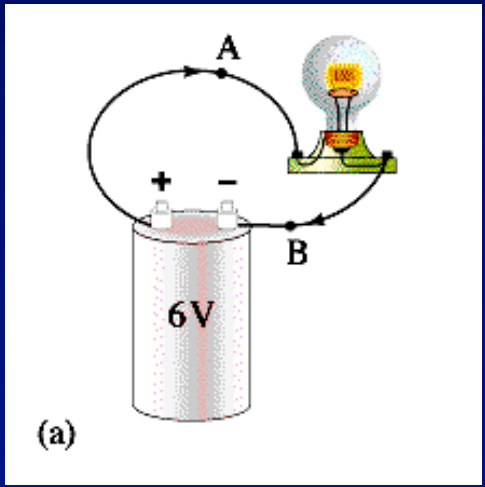
$$v_d = \frac{J}{ne} = \frac{2.04\times10^{6}}{8.4\times10^{28}\times1.6\times10^{-19}} = 1.5\times10^{-4}\,\text{m/s} = 0.15\ \text{mm/s}$$

More current ...

- So in the wire, electrons move (drift) very slowly: on the order of *0.1 mm/s*. Thus, to move 1 meter they need about 3 hours !



- Question: If the electrons move so slowly through the wire, why does the light go on right away when we flip a switch?



Because the electric field inside the wire travels much faster

Electric field travels at the speed of light!

ConcepTest 25.1 Electric currents

- If you have a battery, a light bulb, and only one wire, which is the correct way to light the bulb?

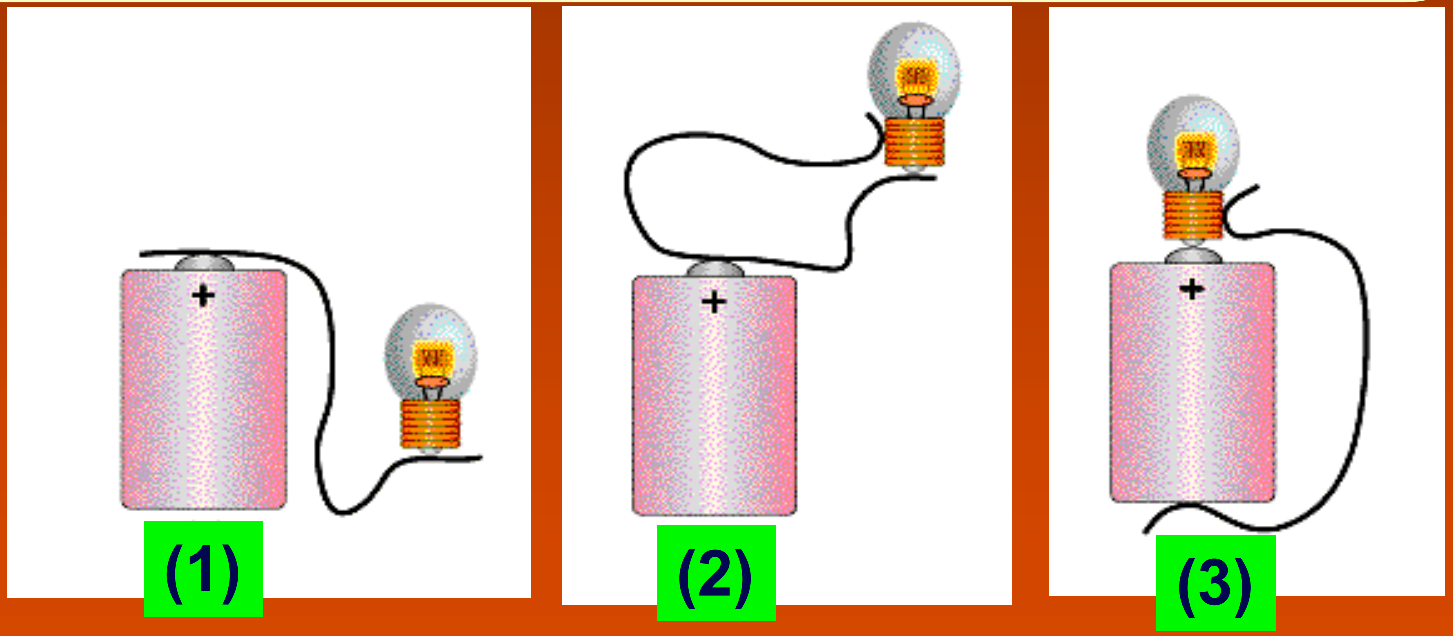
(1) case 1

(2) case 2

(3) case 3

(4) all are correct

(5) none are correct



Resistance and Resistivity

New Topic

Resistivity

- The electric field is directly proportional to the current density in the wire.
- ρ is called resistivity
  - a measure of how much resistance there is for a charge in a material
- SI unit: V.m/A = Ω. m

$$\vec{E} = \rho \vec{J}$$

Table 25.1 Resistivities at Room Temperature (20°C)

	Substance	$\rho(\Omega \cdot m)$	Substance	$\rho(\Omega \cdot m)$
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}

- A perfect conductor has zero resistivity. A perfect insulator has infinite resistivity
- The reciprocal of resistivity (1/ρ) is called conductivity.

Temperature dependence of Resistivity

- The resistivity of a material depends on ***temperature.***

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

(a) Metal: ρ increases with increasing T

(b) Semiconductor: ρ decreases with increasing T

(c) Superconductor: $\rho = 0$ for $T < T_c$

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

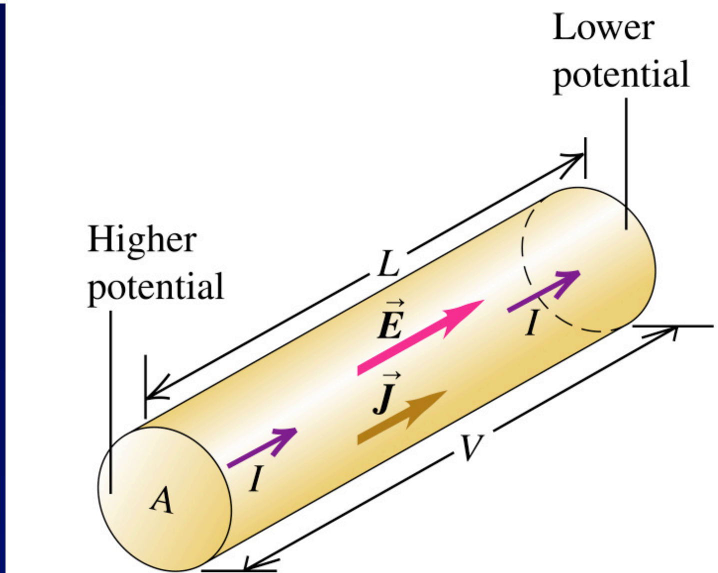
Material	$\alpha\ [(°C)^{-1}]$	Material	$\alpha\ [(°C)^{-1}]$
Aluminum	0.0039	Lead	0.0043
Brass	0.0020	Manganin	0.00000
Carbon (graphite)	−0.0005	Mercury	0.00088
Constantan	0.00001	Nichrome	0.0004
Copper	0.00393	Silver	0.0038
Iron	0.0050	Tungsten	0.0045

Resistance

- **Consider a piece of wire**

$$I = JA \qquad V = EL \qquad E = \rho J$$

$$V = \frac{\rho L}{A} I$$



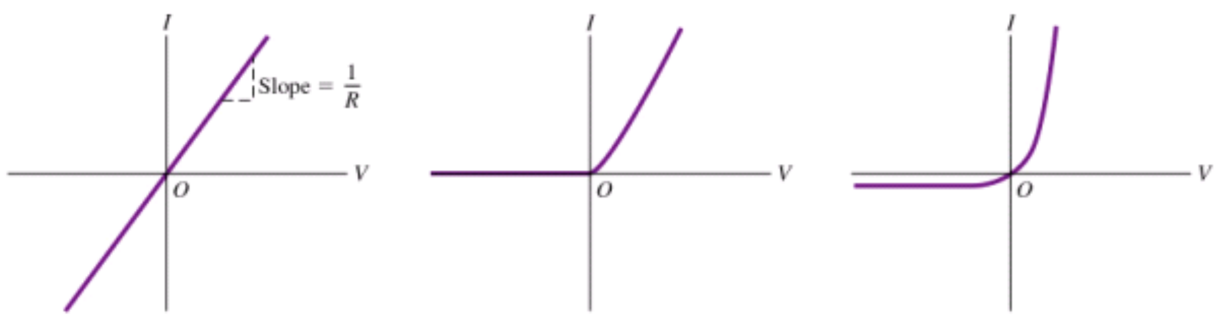
Resistance $$R = \frac{\rho L}{A}$$

Same temperature dependence as ρ

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

Ohm's Law $$V = IR$$

SI unit: 1 V/A = 1 Ω (ohm)



(a) Resistor that obeys Ohm's law

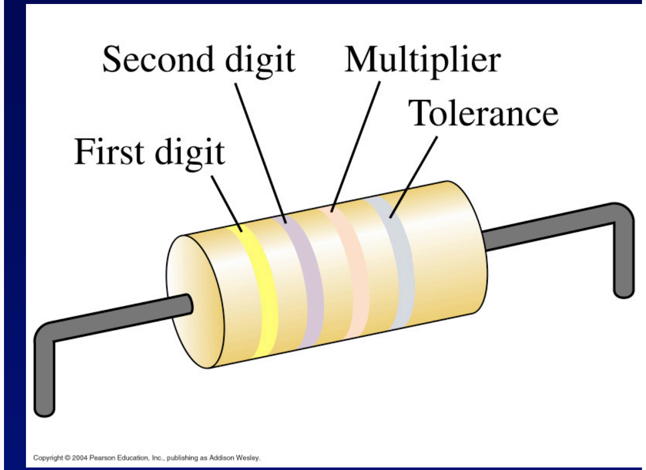
(b) Vacuum diode (does not obey Ohm's law)

(c) Semiconductor diode (does not obey Ohm's law)

Color Coding for Resistors

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



- first two bands are digits
- the 3rd band is power-of-ten multiplier
- the 4th band is the precision
  - no 4th band means 20% uncertainty, silver 10%, gold 5%

- What is resistance of the resistor shown in the picture?

yellow-violet-orange-silver means $47 \times 10^3\ \Omega$, give or take $470\ \Omega$.

ConcepTest 25.2 Ohm's law

- You double the *voltage* across a certain conductor and you observe the *current* increases four times. What can you conclude?

(1) Ohm's law is obeyed since the current increases when V increases

(2) Ohm's law is not obeyed

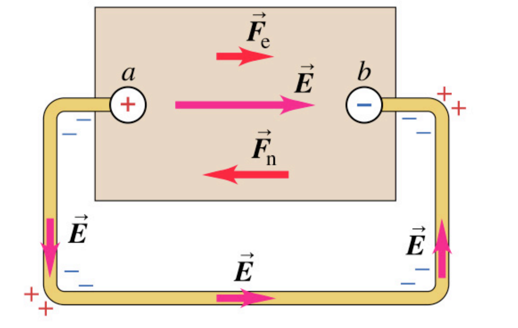
(3) This has nothing to do with Ohm's law

Electromotive Force

New Topic

Electromotive Force (emf)

- To sustain a current flow, there must be a source that can convert other forms of energy into electric potential energy
  - batteries
  - electric generators
  - solar cells
  - …



Source of emf connected to a complete circuit: electric-field force $\vec{F}_e$ has a smaller magnitude than non-electrostatic force $\vec{F}_n$

- The voltage such a source produces is called an emf, denoted by $\mathcal{E}$.

Terminal voltage: $\boxed{V_{ab} = \mathcal{E}}$ **(perfect)**

$\boxed{V_{ab} = \mathcal{E} - Ir}$ **(internal resistance)**

Simple Circuits

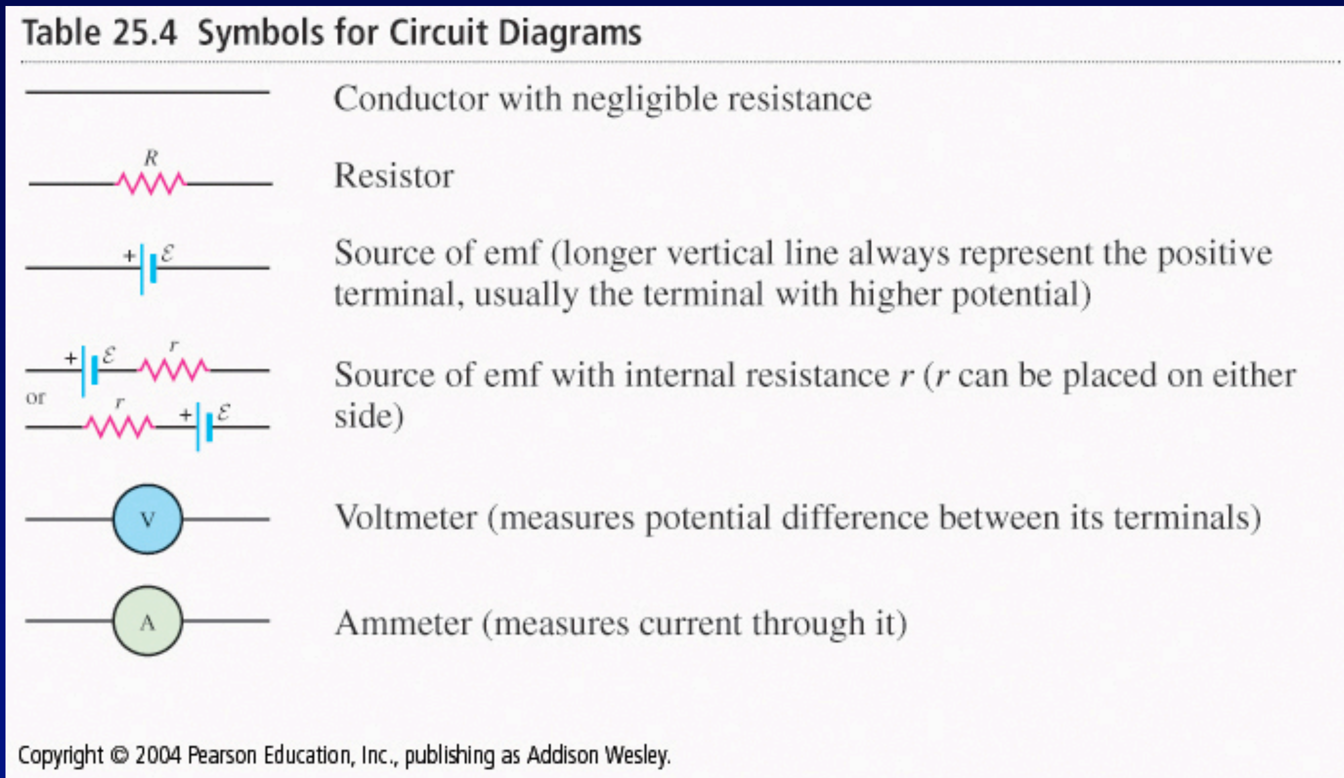


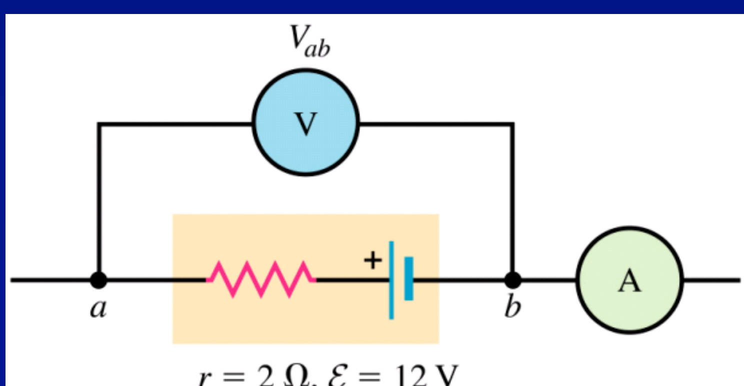
Table 25.4 Symbols for Circuit Diagrams

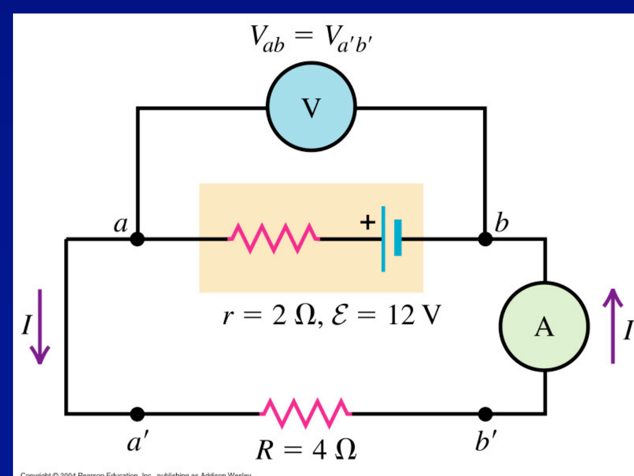
	Conductor with negligible resistance
R	Resistor
$+$ $\mathcal{E}$	Source of emf (longer vertical line always represent the positive terminal, usually the terminal with higher potential)
$+$ $\mathcal{E}$ r or r $+$ $\mathcal{E}$	Source of emf with internal resistance r (r can be placed on either side)
V	Voltmeter (measures potential difference between its terminals)
A	Ammeter (measures current through it)

capacitor
----| |----

Idealized Voltmeter:
infinite resistance

Idealized Ammeter:
zero resistance

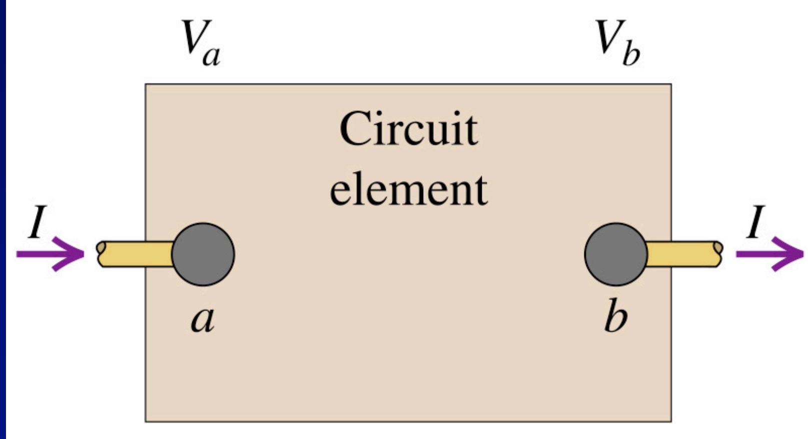




Energy and Power in Electric Circuits

- The work done to move charge $dQ = I\,dt$ across a potential difference of V_{ab} is $dW = V_{ab}\,dQ = V_{ab}\,I\,dt$. Therefore the power delivered is

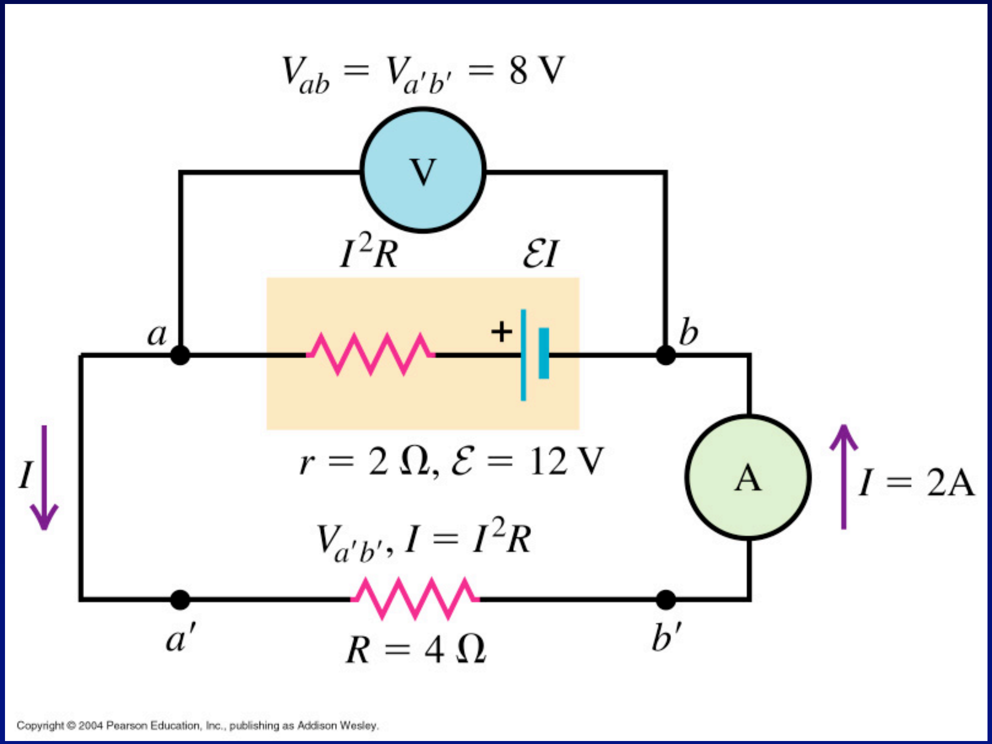
$$\boxed{P = IV_{ab}}$$



For a pure resistor that obeys V=IR, one can write

$$\boxed{P = IV_{ab} = I^2R = \frac{V_{ab}^2}{R}}$$

Example: power counting in a circuit



- Power of energy conversion in the battery is $\mathcal{E}$ I= 12 x 2 =24 W
- Power loss in the internal resistor is $I^2 r$ = 4x2 = 8 W
- Power output of the battery is 24-8 = 16 W
- Power loss in the outside resistor is $I^2 R$ = 4x4 = 16 W

ConcepTest 25.3 emf

- The picture shows an open circuit. What's the reading on the Voltmeter and Ammeter?

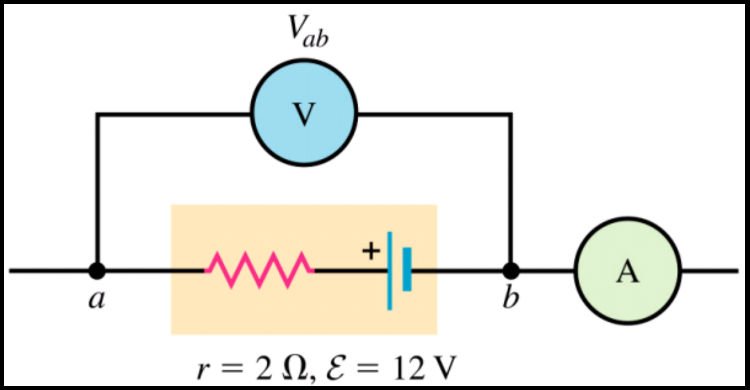
(1) V_{ab}=12 V, I=0 A

(2) V_{ab}=0 V, I=6 A

(3) V_{ab}=12 V, I=6 A

(4) V_{ab}=0 V, I=0 A

(5) None of these



ConcepTest 25.4 Power Lines

For long wires, the resistance of power lines becomes significant. To transmit maximum power, is it better to transmit ***high V, low I*** or ***high I, low V*** ?

a) high V, low I

b) low V, high I

c) makes no difference