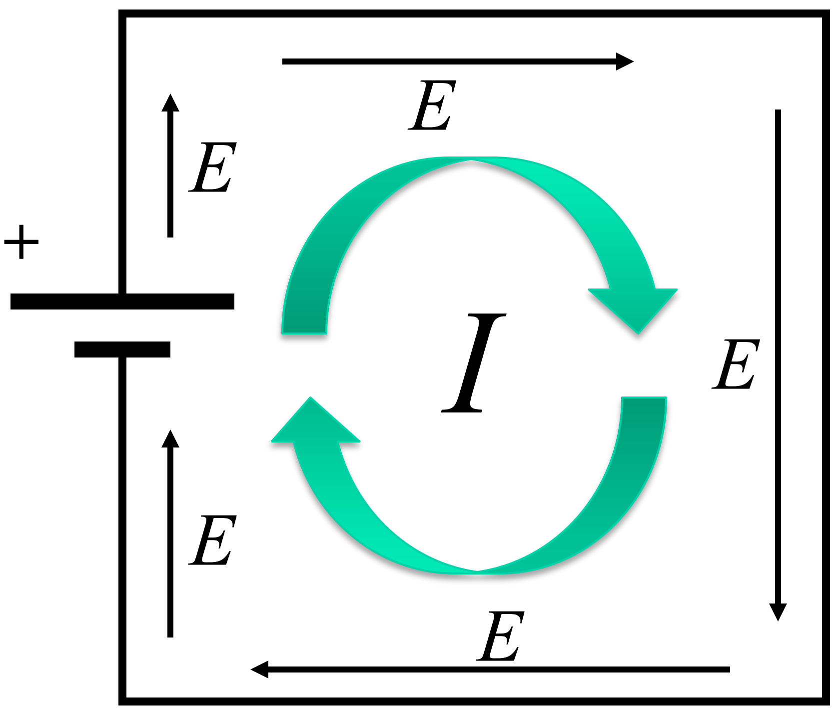
Chapters 24/25: Current, Circuits & Ohm's law
Thursday September 29th

****Register your *i*Clickers****

- Conductors under dynamic conditions
  - Current, current density, drift velocity
- Ohm's law
- Types of conductor
  - Semiconductors and superconductors
- Microscopic basis for Ohm's law
- DC circuits
  - Kirchoff's 2nd law
  - Energy transfer in DC circuits

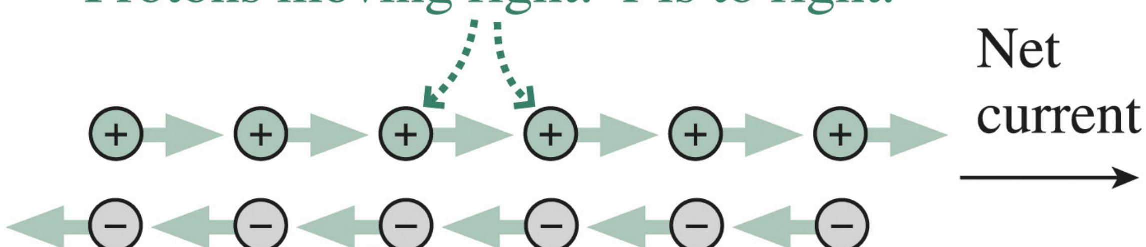
Reading: up to page 419 in the text book (Chs. 24/25)

Conductors in E-fields: dynamic conditions



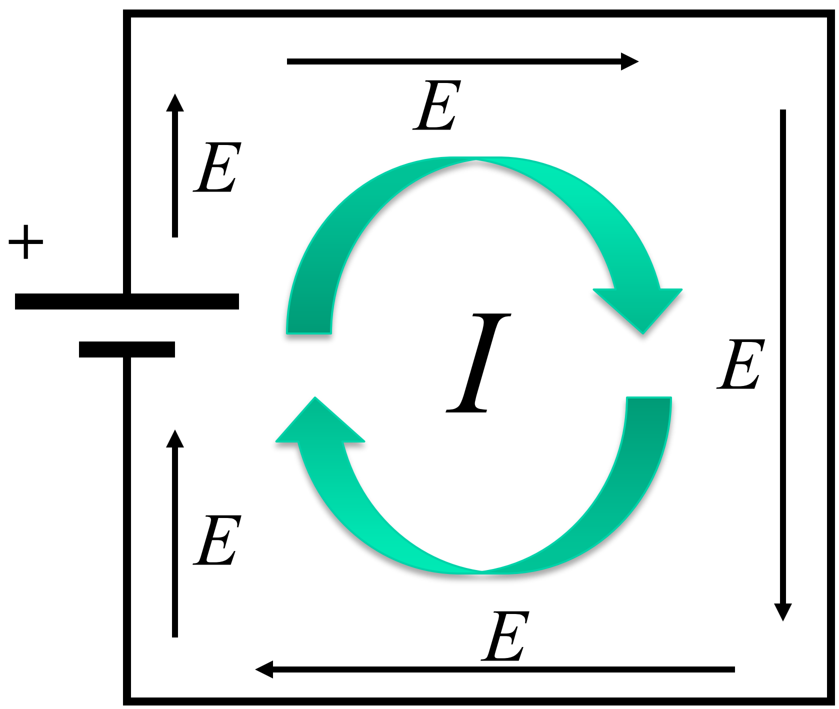
- ***If the E-field is maintained, then the dynamics persist, i.e., charge continues to flow indefinitely.***
- ***This is no longer strictly the domain of electrostatics.***
- ***Note the direction of flow of the charge carriers (electrons).***

Protons moving right: *I* is to right.



Negative electrons moving left: *I* is to *right*.

Conductors in E-fields: dynamic conditions



- ***If the E-field is maintained, then the dynamics persist, i.e., charge continues to flow indefinitely.***
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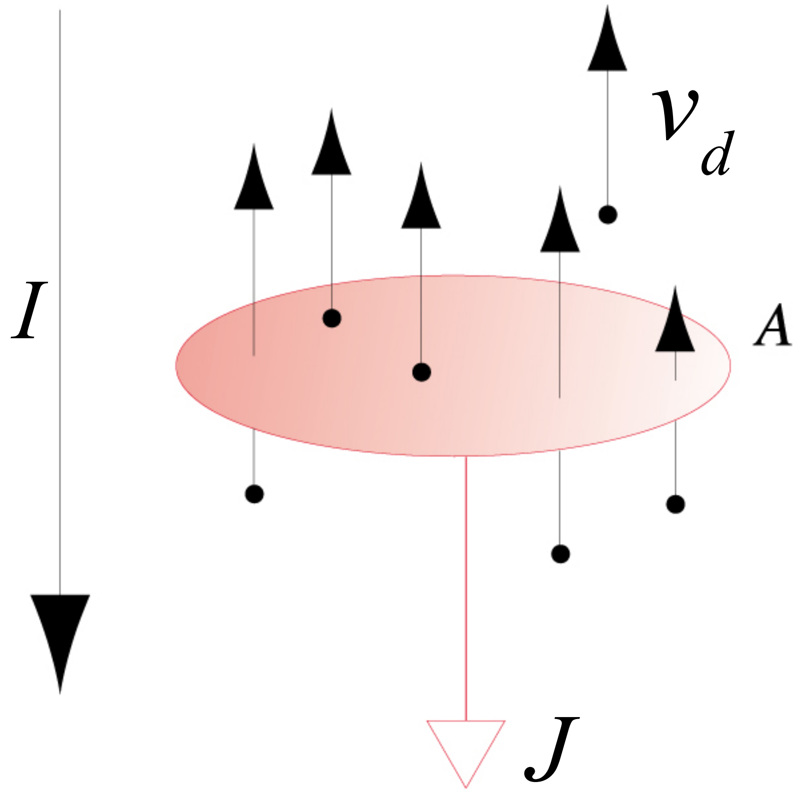
- ***Note the direction of flow of the charge carriers (electrons).***

Electrical current: $$I = \frac{dQ}{dt} \approx \frac{\Delta Q}{\Delta t}$$

SI unit: 1 ampere (A) = 1 coulomb per second (C/s)

Conductors in E-fields: dynamic conditions



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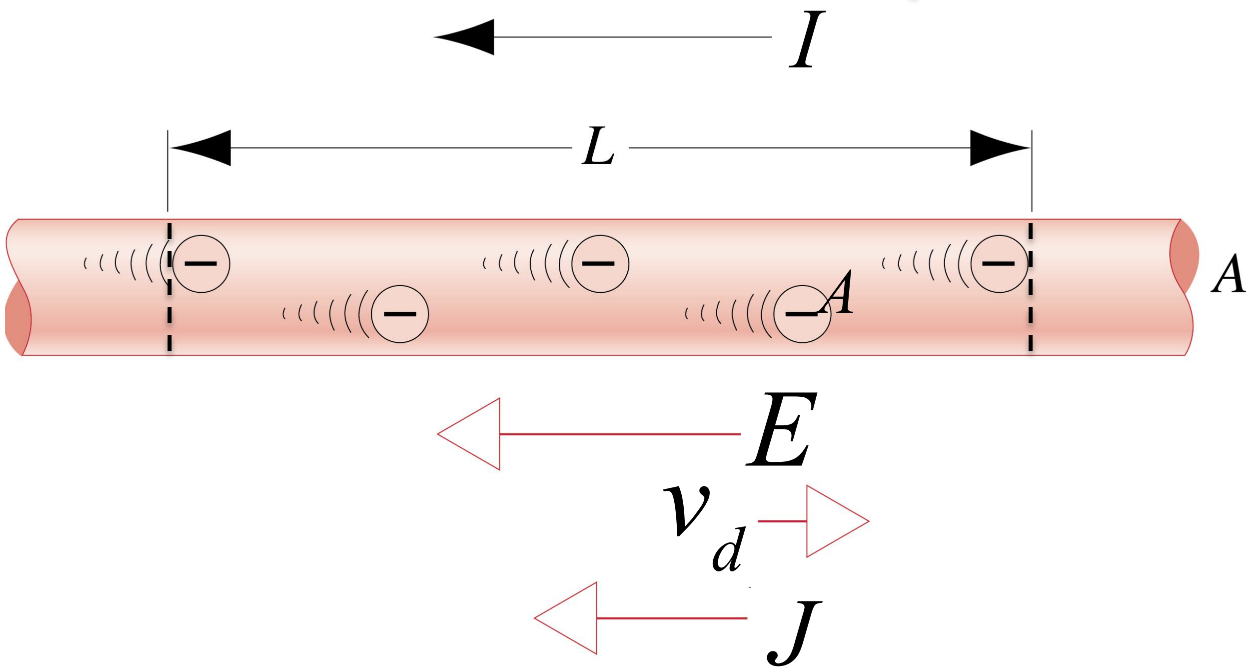
Current density: $J = \dfrac{I}{A}$ or $\dfrac{dI}{dA}$

Current: $I = \int \vec{\boldsymbol{J}} \cdot d\vec{\mathbf{A}} = J \times A$

Current density and drift speed



$Q = -e$ (charge per carrier)

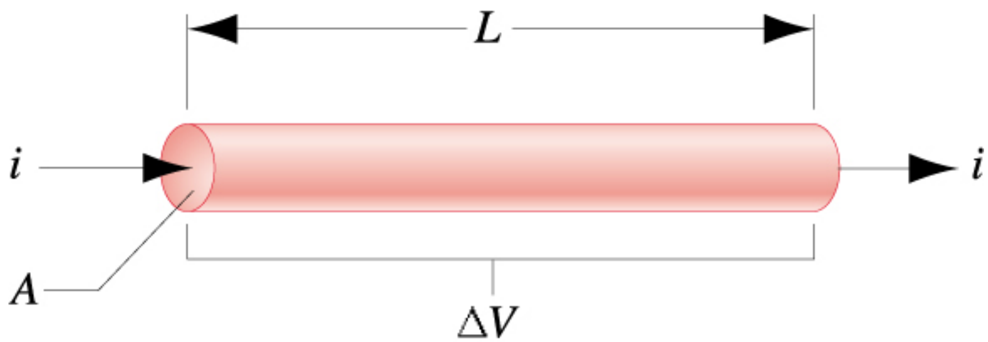
n = number of carriers per unit volume

$$J = nQv_d$$

$$I = nQv_d A$$

Starting point for Ohm's Law

Ohmic materials (Ohm's law)



- ***We will see that v_d is proportional to E. Thus, J is proportional to E.***

$$\vec{J} = \sigma \vec{\mathbf{E}}$$

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

Ohm's Law (empirical)

σ is the electrical conductivity

ρ is the electrical resistivity

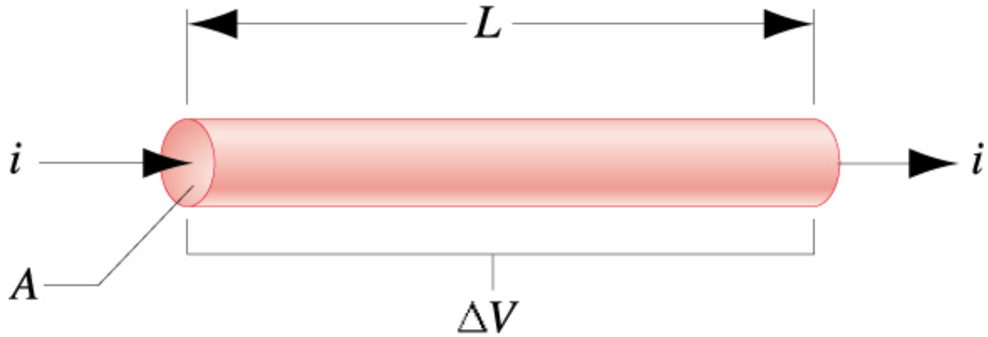
$$\sigma = \frac{1}{\rho}$$

SI unit for resistivity is *ohm - meter*: 1 ohm = 1 volt/ampere

SI unit for conductivity is *siemens per meter*:

1 siemens = 1 ampere/volt = $(1 \text{ ohm})^{-1}$

Ohmic materials (Ohm's law)



- ***We will see that v_d is proportional to E. Thus, J is proportional to E.***

$$\vec{J} = \sigma \vec{\mathbf{E}}$$

Ohm's Law

(microscopic)

Resistance: $R = \dfrac{\rho L}{A}$

SI unit for resistance is *ohm* (Ω)

$$I = \frac{1}{R} V$$

Ohm's Law

(macroscopic)

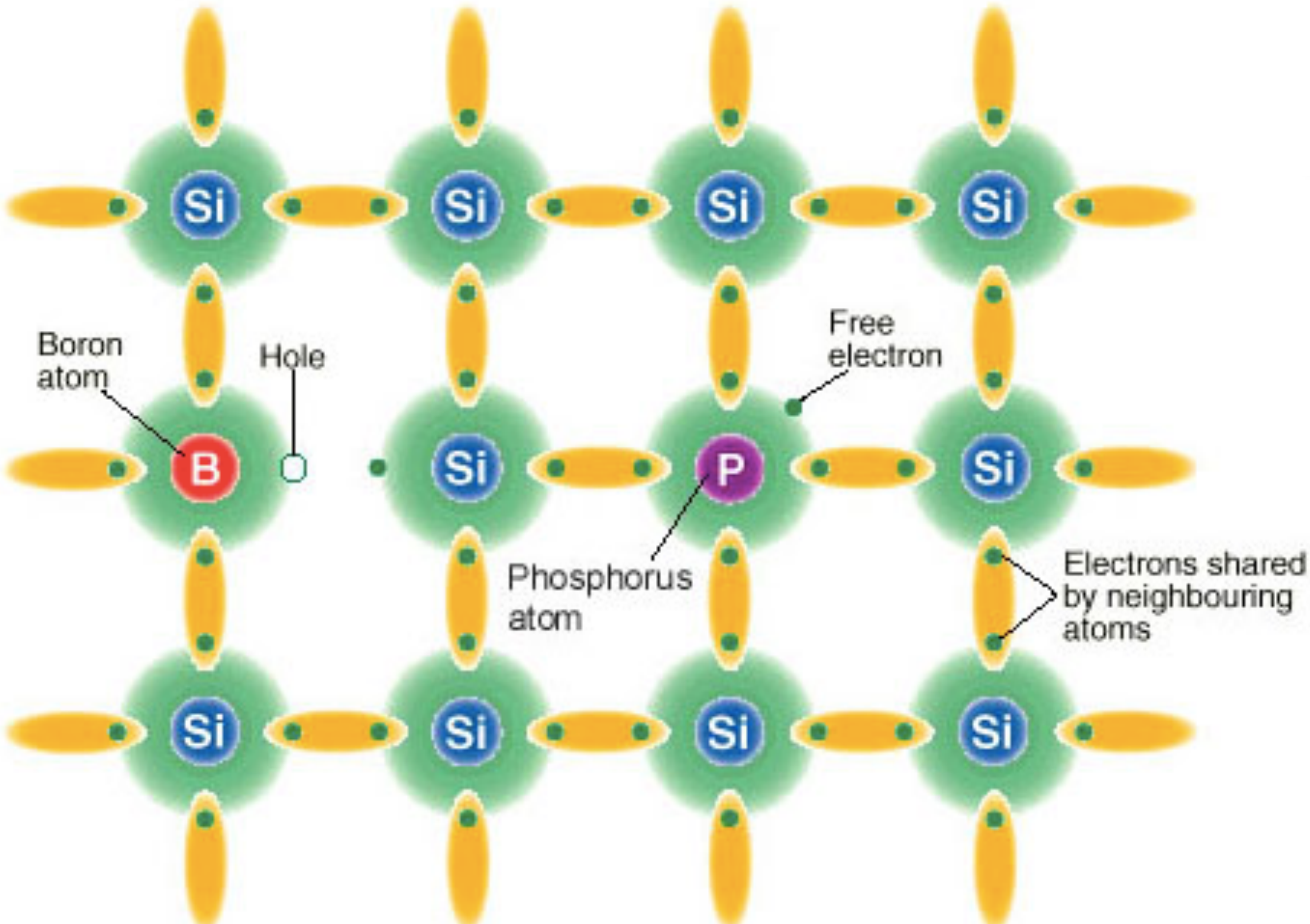
Semiconductors

- In a metal (conductor), not all of the electrons are directly involved in the chemical bonding; thus they are relatively free to move.
- In an insulator all electrons are involved in bonding.

Dopants/
Impurities

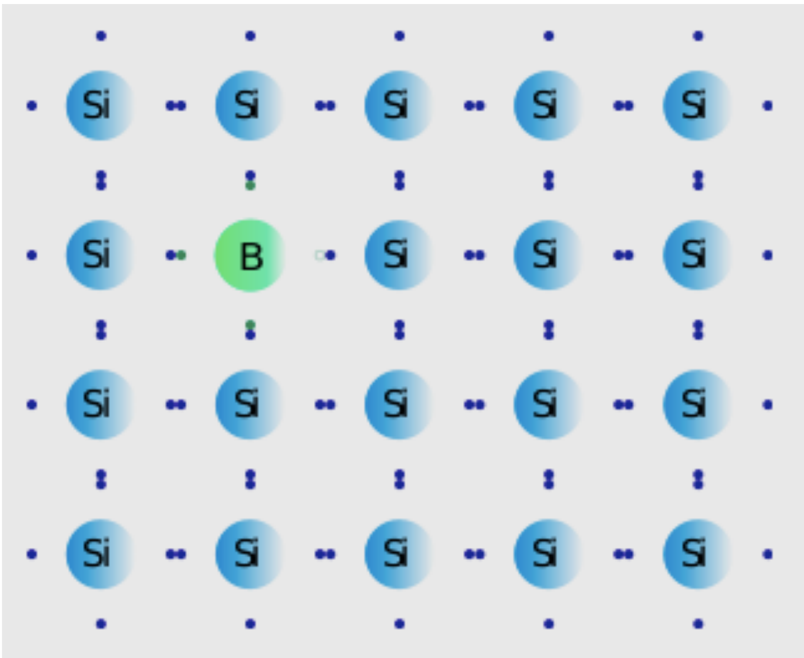
5 B	6 C	7 N
13 Al	14 Si	15 P
31 Ga	32 Ge	33 As

Si: [Ne]$3s^2 3p^2$
B: [He]$2s^2 3p^1$
P: [Ne]$3s^2 3p^3$

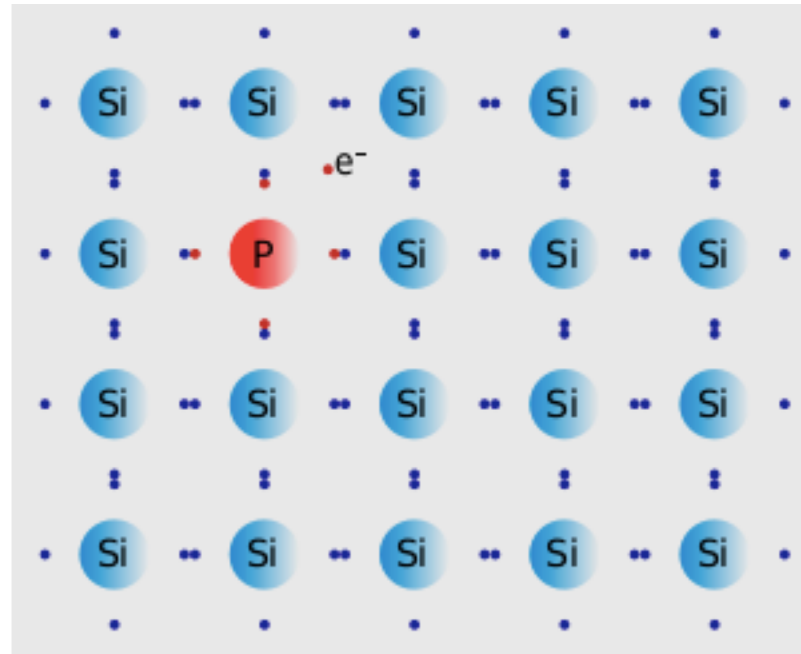


Semiconductors

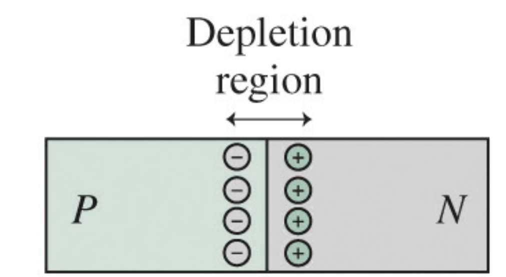
p-type (mobile holes (+))

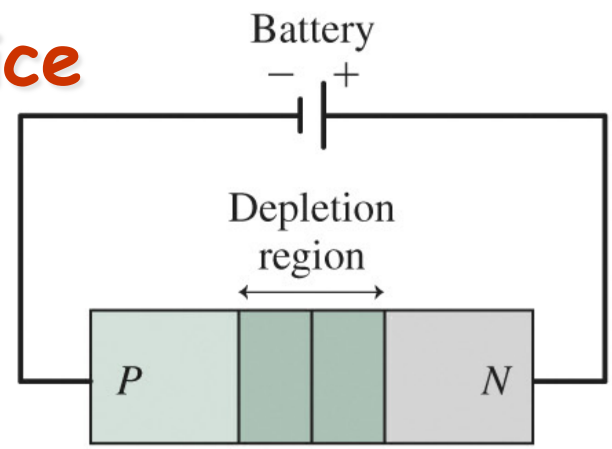


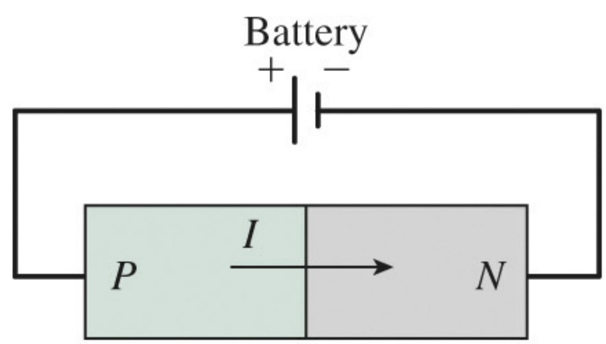
n-type (mobile holes (−))



Junction device

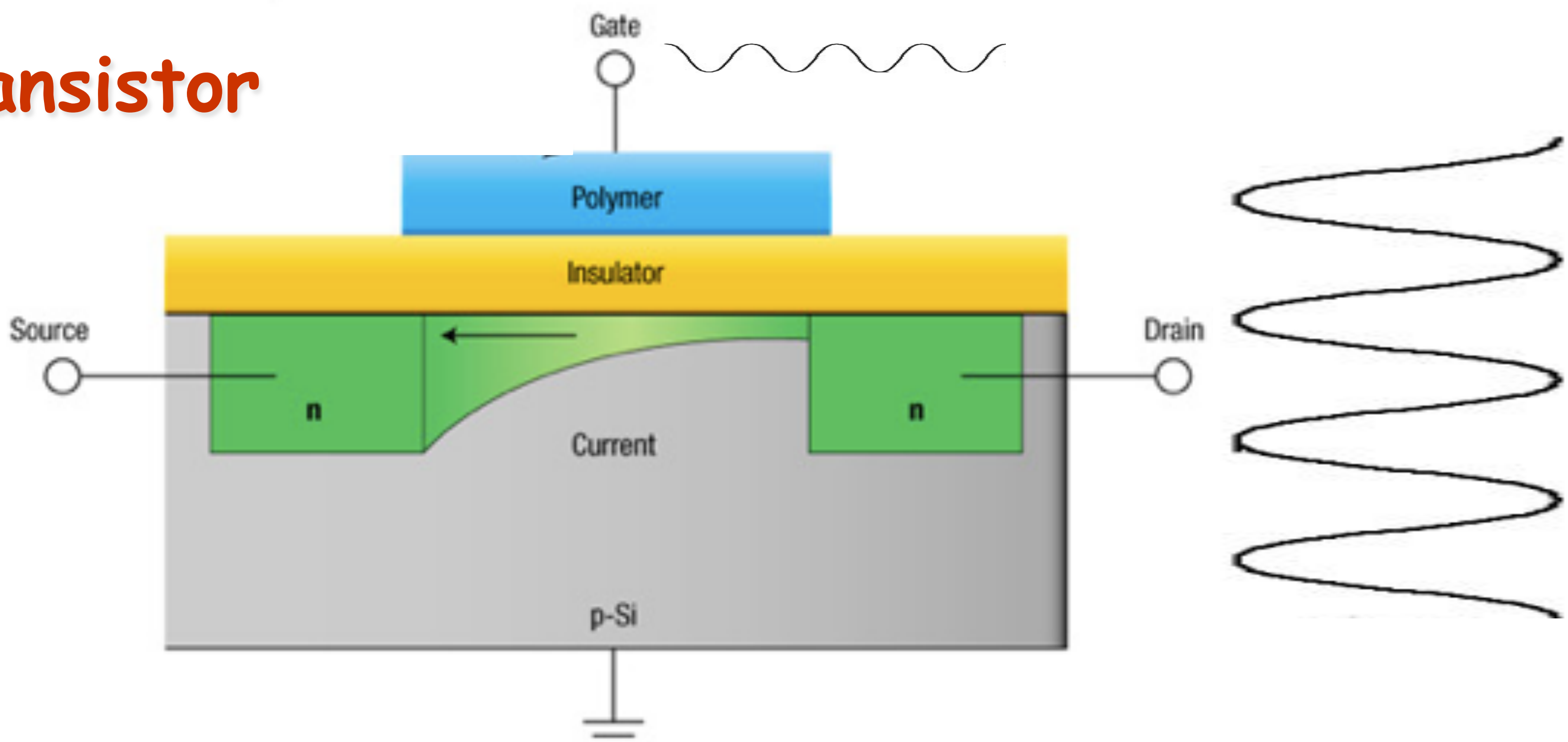




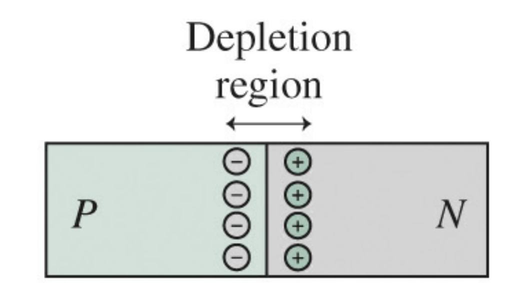


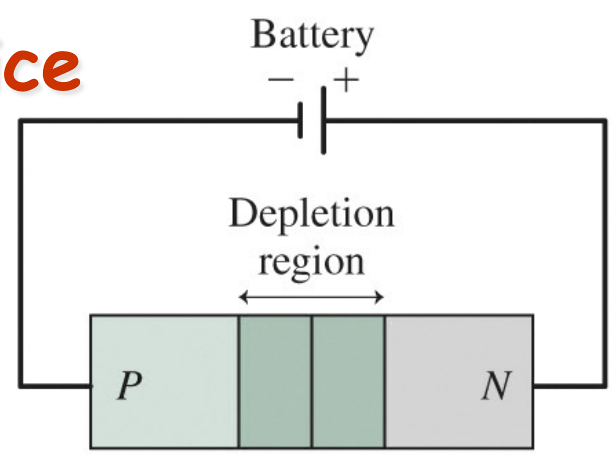
Semiconductors

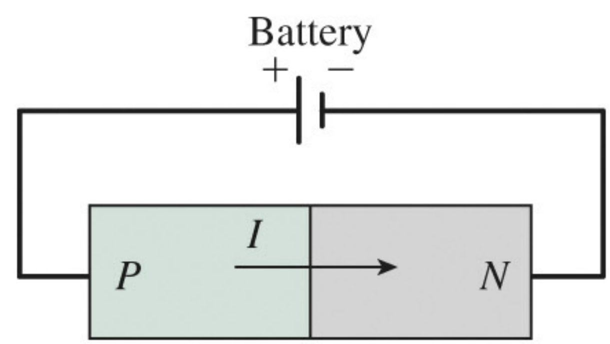
Transistor



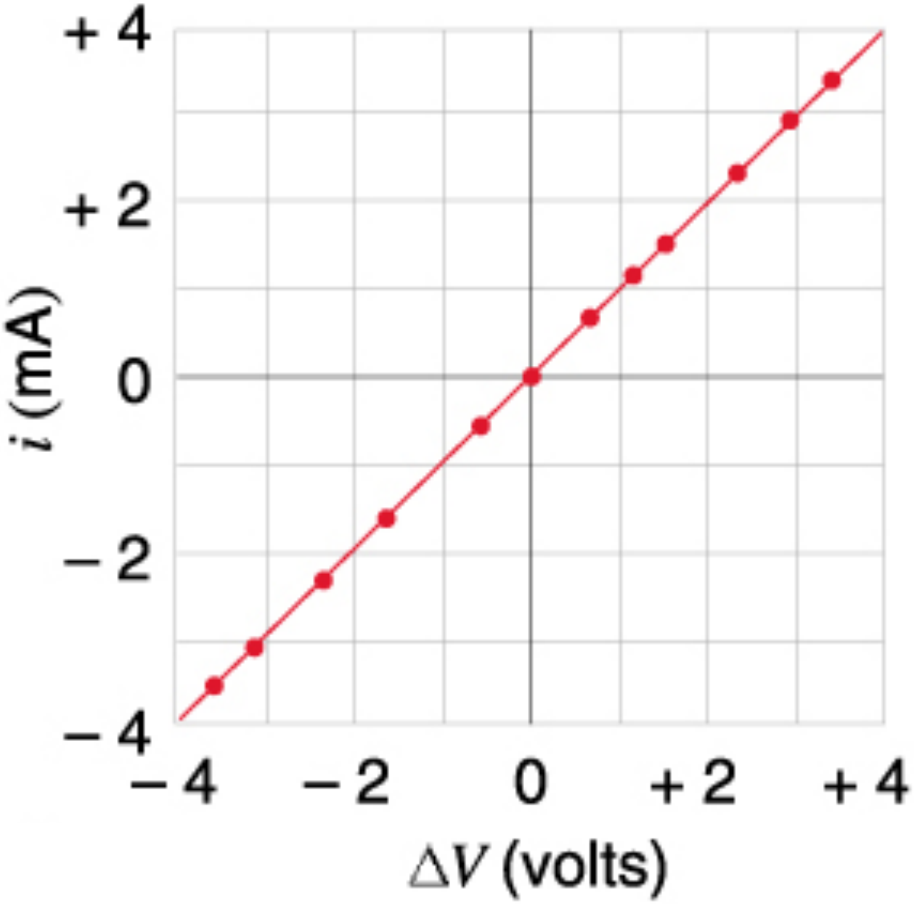
Junction device

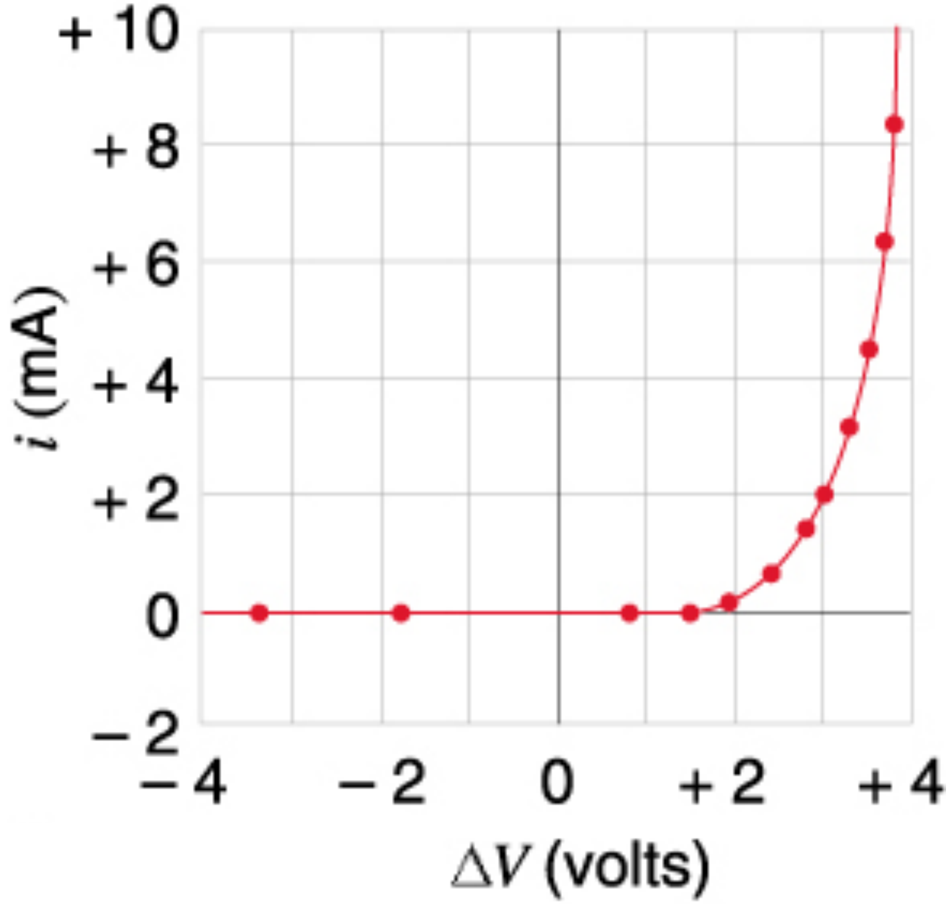






Ohmic materials (Ohm's law)





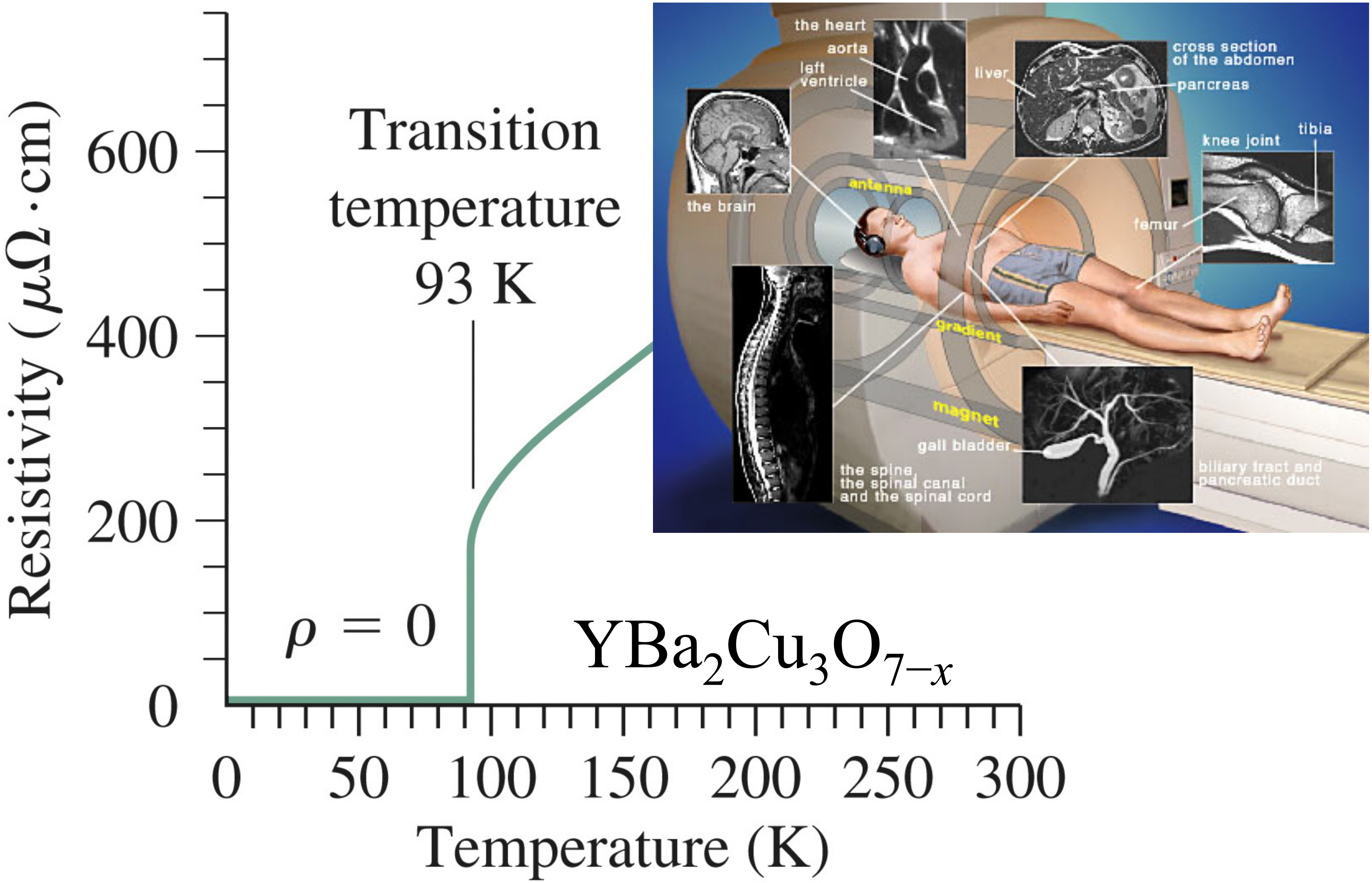
Ohmic **Non-ohmic**

Ohmic materials (Ohm's law)

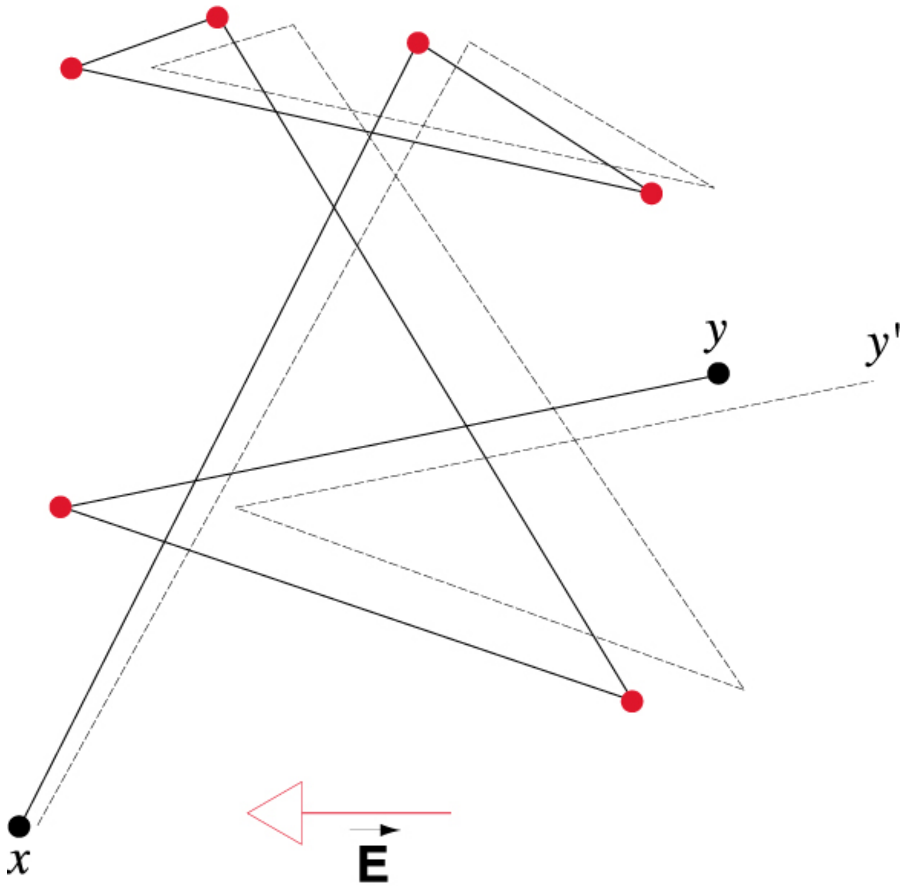
Table 24.1 Resistivities

Material	**Resistivity** ($\Omega \cdot m$)
Metallic conductors (20°C)	
Aluminum	2.65×10^{-8}
Copper	1.68×10^{-8}
Gold	2.24×10^{-8}
Iron	9.71×10^{-8}
Mercury	9.84×10^{-7}
Silver	1.59×10^{-8}
Ionic solutions (in water, 18°C)	
1-molar $CuSO_4$	3.9×10^{-4}
1-molar HCl	1.7×10^{-2}
1-molar NaCl	1.4×10^{-4}
H_2O	2.6×10^{5}
Blood, human	0.70
Seawater (typical)	0.22
Insulators	
Ceramics	10^{11}–10^{14}
Glass	10^{10}–10^{14}
Polystyrene	10^{15}–10^{17}
Rubber	10^{13}–10^{16}
Wood (dry)	10^{8}–10^{14}

Superconductivity

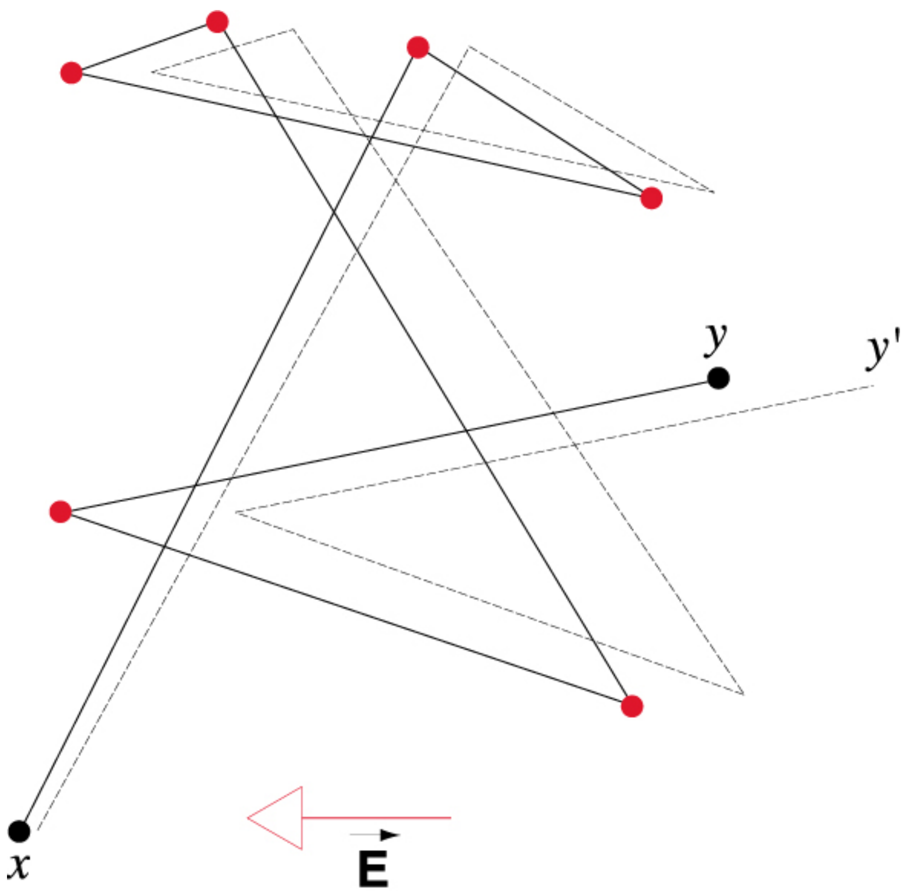


Ohm's law: a microscopic view



- The average ***speed*** of an electron in a metal is about 10^6 m/s. This is almost 1% of the speed of light!!
- So, how is this reconciled with the calculated drift ***velocities*** of order 10^{-4} m/s (for a current of 1A)?

Ohm's law: a microscopic view



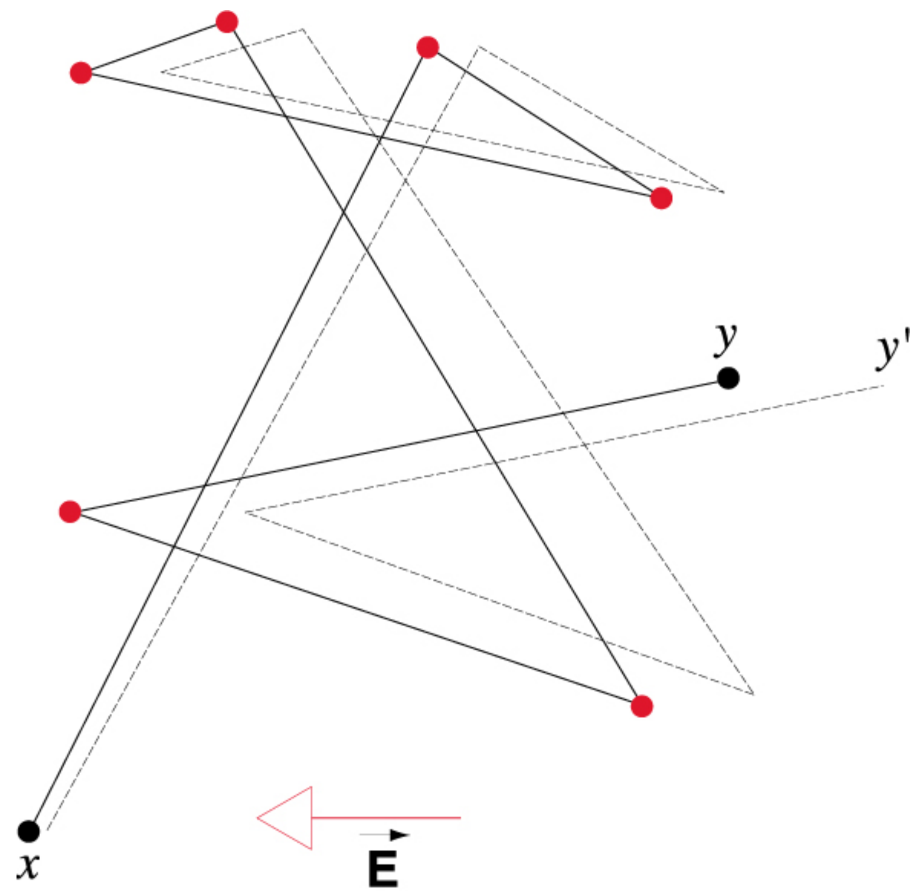
Repeated collisions average electron ***velocities*** to zero. Upon application of electric field, electrons accelerate. However, collisions quickly dissipate any acquired momentum. Consequently, the electrons slowly drift in the direction opposite to the field.

$$Force = \frac{\Delta p}{\Delta t} = eE = \frac{m\langle \Delta v \rangle}{\tau}$$

τ is the average time between collisions, and m is the electron mass.

The average change in velocity, $\langle \Delta v \rangle$, turns out to be equivalent to the resultant drift velocity v_d of the ensemble of electrons.

Ohm's law: a microscopic view



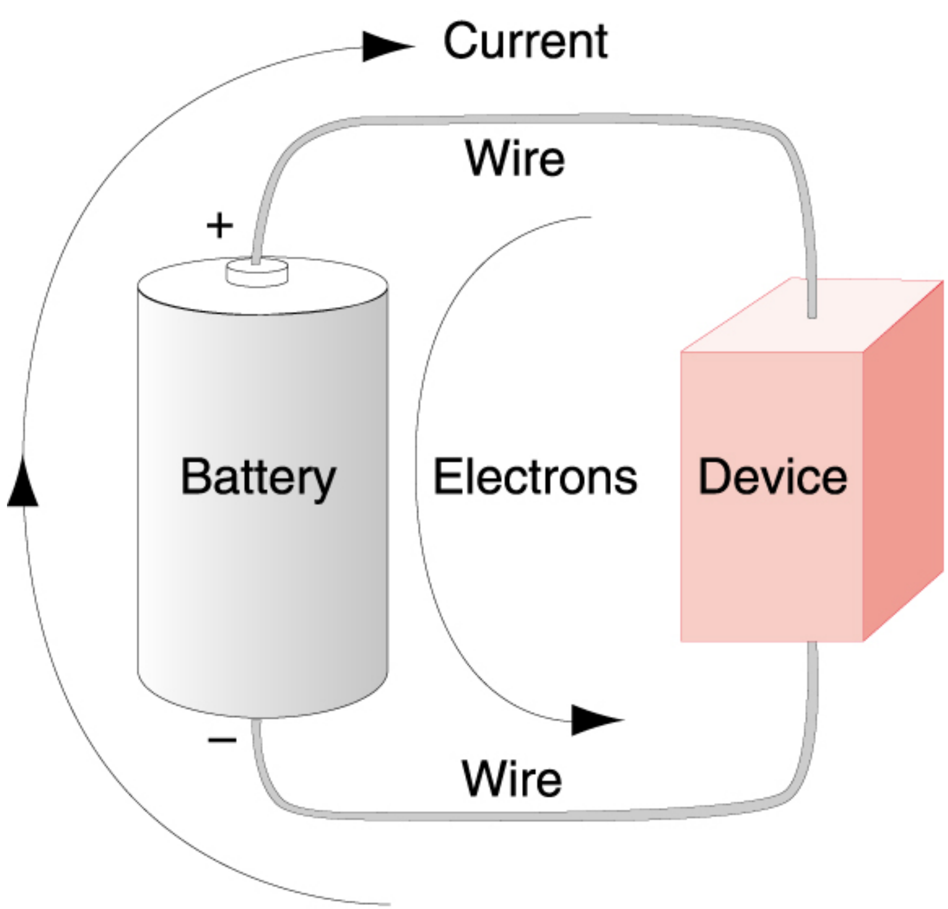
Repeated collisions average electron ***velocities*** to zero. Upon application of electric field, electrons accelerate. However, collisions quickly dissipate any acquired momentum. Consequently, the electrons slowly drift in the direction opposite to the field.

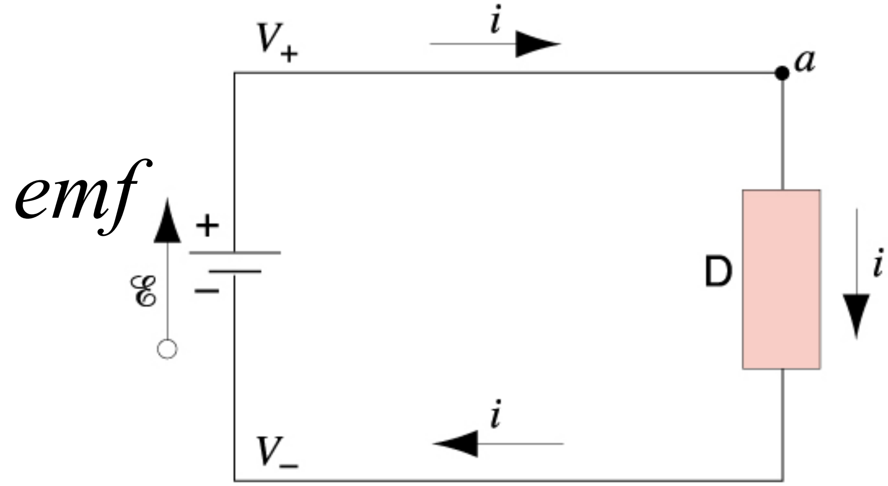
$$v_d = \left(\frac{e\tau}{m}\right)E$$

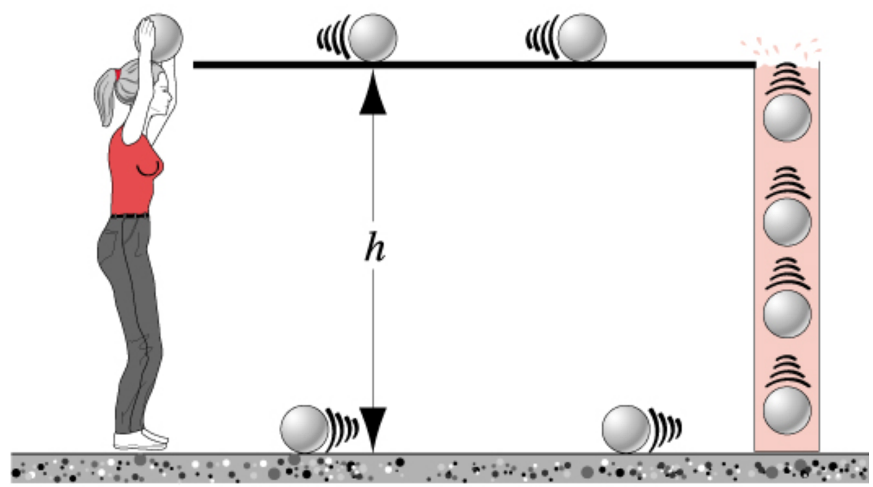
$$j = env_d = \left(\frac{ne^2\tau}{m}\right)E = \sigma E$$

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

DC Circuits







EMF = electromotive force

Electromotive force (emf)

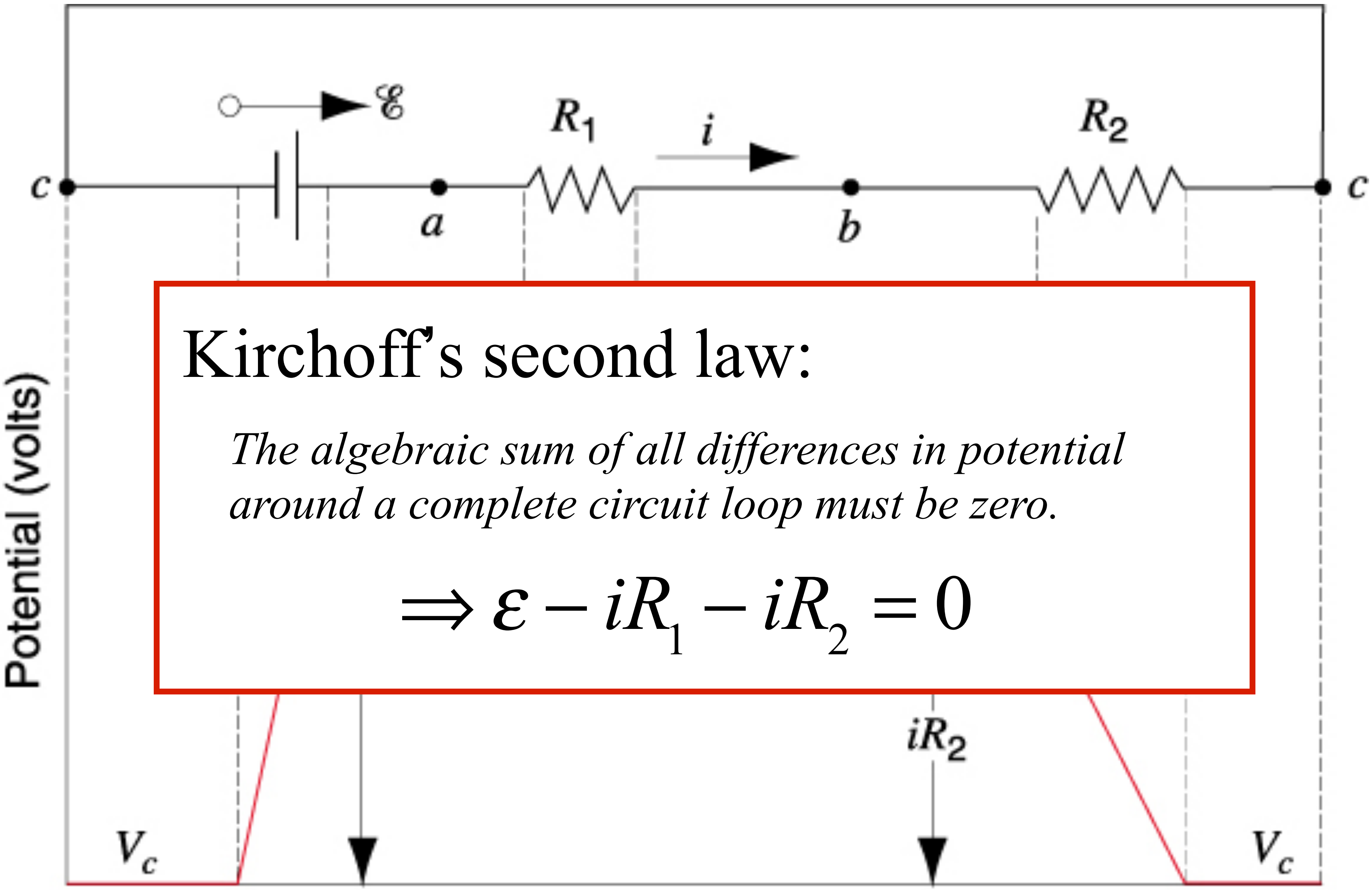
- **Source of electrical energy in a circuit.**

$$\varepsilon = dW \, / \, dQ$$

SI unit: joule/Coulomb

- Represents the potential energy provided to each coulomb of charge that passes through the device.
- IT IS NOT A FORCE!!!
- Most often, emf is provided by a battery (a chemical cell).
- The emf is the same as the potential difference between the negative and positive terminals of a battery **WHEN NO CURRENT FLOWS**.
- In general, when a current flows, the potential difference at the terminals of a battery is lower than the emf.
- An emf can also store energy.

Circuit analysis



Kirchoff's second law:

The algebraic sum of all differences in potential around a complete circuit loop must be zero.

$$\Rightarrow \varepsilon - iR_1 - iR_2 = 0$$

Energy transfer in electric circuits

- A 1V battery does work by providing each coulomb of charge that leaves its positive terminal 1 joule of energy.
- If charge flows at a rate of 1 coulomb per second, then the battery does work at a rate of 1 joule per second, i.e.

$$\text{Power} = \frac{\text{joule}}{\text{coulomb}} \times \frac{\text{coulomb}}{\text{second}} = \frac{\text{joule}}{\text{second}} = \text{watt}$$

$$P = \varepsilon I = dW / dt$$

- In a resistor, energy is lost in an amount *iR* per coulomb.

$$\Rightarrow P_{charge} = I \times \Delta V = I\left(-IR\right) = -I^2 R$$

$$P_{heat} = I^2 R = \left(V / R\right)^2 R = V^2 / R$$

- This process is irreversible.