Goal of this chapter is to learn how we model the electron motions in conductors, and how it relates to electric current.

- Remember in Chapter 22, and 23, we learned that in charged conductors, the electric field, $\vec{E}$, inside the conductor is 0 (Review Example 22.5); while the electric potential, V, is a constant value everywhere in the conductor and the same as the value on the surface (Review Example 23.8).
- The above argument is only valid for equilibrium condition, which means each charge reaches the equilibrium position (charges are not moving). However, in the case where electric field is non-zero inside the conductor, charges will move according to the electric field direction (or depends on the electric potential).


Electric current is defined as how much Positive charge passing through a certain cross-section of materials

$$I = \frac{dQ}{dt}$$
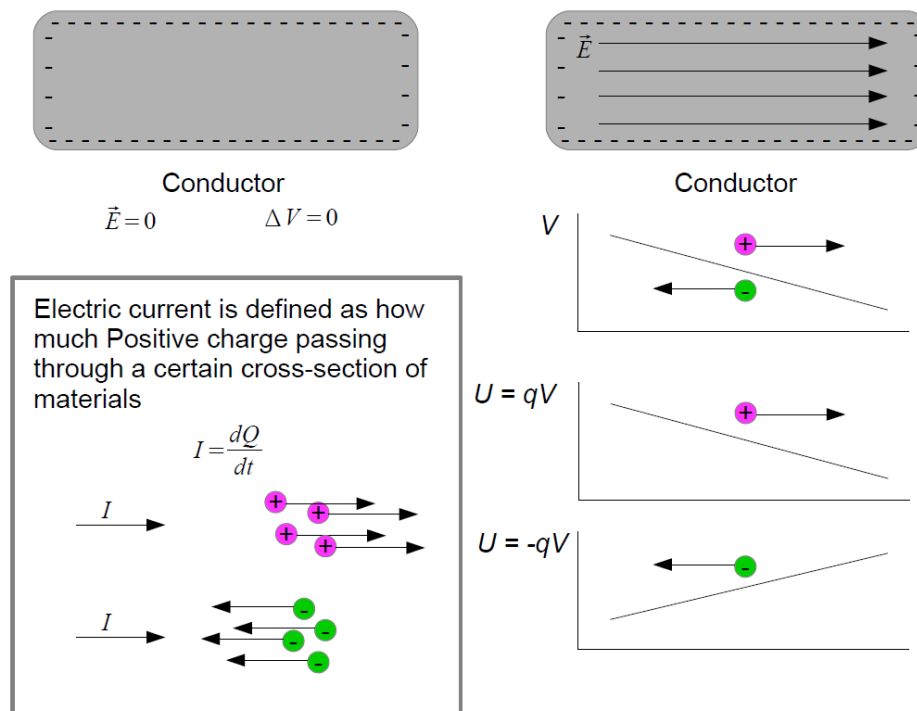
- Electric field, $\vec{E}$, has the same direction as electric current, *I*, despite the sign of the moving charges.
- Electric current, *I*, flows from high electric potential toward low electric potential.
- NOTE: the direction of the electric current is not necessary the same as the moving charges (they are opposite when the moving charges are negative).

- The unit of the electric current is A (ampere), defined as:

$$1\,A = 1\frac{C}{s} = 1\,(coulomb\ per\ second)$$

➢ **How are those charges (electrons, in fact) move in conductors?**

- Electrons move in conductors just like gas molecules move in air – **Brownian motion**.


$$v_d \Delta t$$
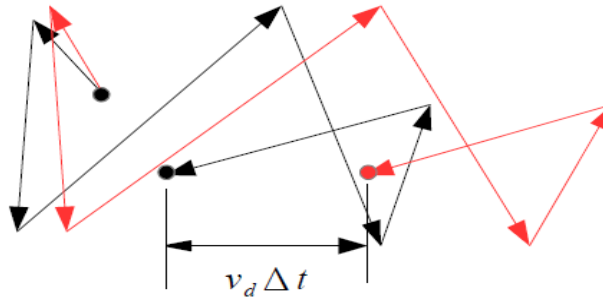
Black: Electron motion without electric field.

Red: Electron motion with electric field pointing to the left.

- Just like Brownian motion for gas molecules, every turning point represents a collision (interaction) with something, which could be ions, defects etc. In principle, each collision will take out certain portion of energy carried by the electron.
- The transferred energy typically will become heat.
- This random walk with collision events are the cause of electric resistance, R, or resistivity, ρ .
- The distance that attained by the presence of the electric field is calculated as: $\vec{v}_d \Delta t$. where Δt is the time passed; $\vec{v}_d$ is called drift velocity.
- Drift velocity, $\vec{v}_d$, is the velocity attained by the presence of the electric field.

- The electric current could be expressed as: $I = \dfrac{dQ}{dt} = n|q||\vec{v}_d|A$. where n is the density of the charge per unit volume (how many particles per unit volume); $|q|$ is the amount of charge per particle; A is the cross section for the charge to pass through.

- Current density (J): $\vec{J} = \dfrac{I}{A} = n\,q\,\vec{v}_d$. (Current per unit area)
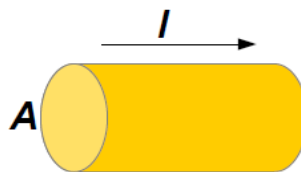
- How do we describe the "*collisions*" that prevent electrons from moving forward?
**Ohm's law**

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

- The greater the resistance, R, is, the higher the electric potential, V, needed to drive a given current, I.
- Note: the unit of the resistance is Ohm, Ω, defined as: $1\Omega = 1\,V/A$.
- Resistance, R, depends on the size and length of the conducting wire, and also on the choice of the material. **How to find a quantity that is only related to the material?**

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

- Resistivity, ρ, is a material related property (see Table 25.1 on page 823). It also follows Ohm's law as:

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

- The unit of resistivity is $\Omega \cdot m$. Why? See here: $\dfrac{V/m}{A/m^2} = \Omega \cdot m$.

- In fact, the value of resistivity, hence the resistance, is a function of temperature. And the dependence on the temperature varies for different types of materials.

| ρ (Metal) | ρ (Semiconductor Or Insulator) | ρ (Superconductor) |
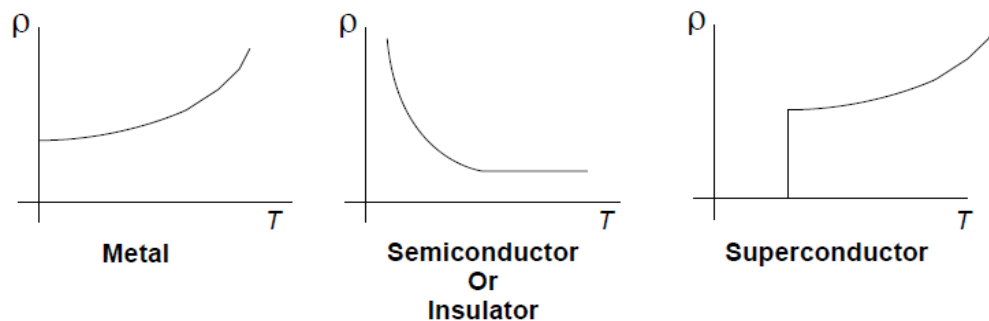
- The temperature dependence, as you can see, is very complicate.
- What we can do for now, is to use some approximation to describe resistivity (hence resistance) in metal.
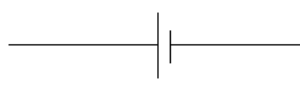
$$\rho(T) = \rho_0[1 + \alpha(T - T_0)]$$
$$R(T) = R_0[1 + \alpha(T - T_0)]$$

- ρ_0 and R_0 are the resistivity and resistance, respectively, at reference temperature T_0.

You Do Example 25.2 on page 827
**I Do Problem 25.18, 25.21 on page 844**

- Symbols in circuit

————————	Ideal wire (negligible resistance)
—⟋⟍⟋⟍⟋⟍—	Resistor
——||———	Ideal emf source (no internal resistance)
—[⟋⟍⟋⟍⟍||]—	emf source (with internal resistance)
——||———	Capacitor
——(A)———	Ammeter (measure current through it)
——(V)———	Voltmeter (measure potential different at the two terminal)

- Electric potential pump: Electromotive Force (emf) source
  • Remember, electrons always move toward lower electric potential energy direction (higher electric potential, since electron has negative charge, see the beginning of this document).
  • In a circuit, if the current keeps flowing, that means there must be something in the circuit serves as electric potential pump, which provides the emf to pump the electrons at lowest energy to certain value.
  • These devices include, but not limited to, battery, power supply etc.
  • Since most materials have resistance, and the fact that these emf devices are made of materials, they have some "*internal resistance*". So the output voltage depends on the output current, emf, and the internal resistance as:
  $$V = \epsilon - I \cdot r$$
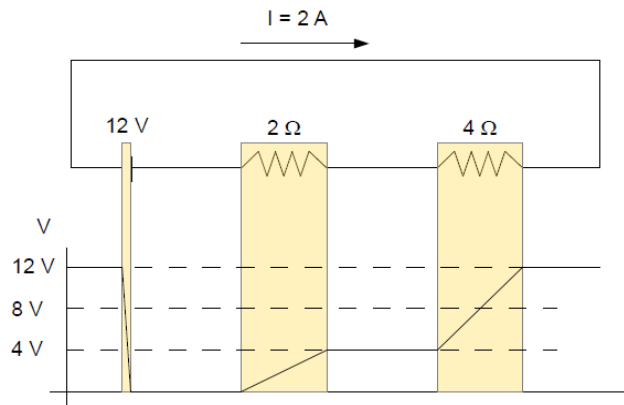
You Do Example 25.5 and 25.6 (a) on page 832
I Do Problem 25.35 on page 845

- We learned in Chapter 23, the electric potential energy is defined as: $U = qV$. How to know the power (energy delivered per unit time) in circuit?

- $P = IV = \dfrac{dQ}{dt} V$

- The unit is watt: $1W = 1\dfrac{C}{s} \cdot \dfrac{J}{C}$

- Use Ohm's law, $V = IR$, power could be written in three different ways:

  $P = IV = I^2 R = \dfrac{V^2}{R}$

You Do Example 25.8 on page 836
I Do Problem 25.46 on page 845

Skip section 25.6

Math Preview for Chapter 26:
- Nothing special

Question to think:
- Think: What is the nature of current and voltage? When we are analyzing a complex circuits containing many different devices, do you have a good idea how the voltage and current are distributed over these devices?