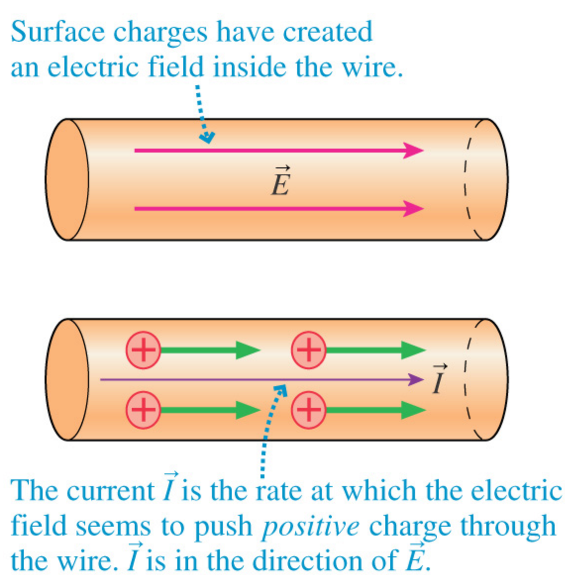
PHY294H

- Professor: Joey Huston
- email:huston@msu.edu
- office: BPS3230
- Homework will be with Mastering Physics (and an average of 1 hand-written problem per week)
  - **Problem 29.77 (already assigned) will be the hand-in problem for 4th MP assignment (due Wed Feb. 10)**
  - **Help-room hours: 12:40-2:40 Tues; 3:00-4:00 PM Friday**
- Quizzes by iclicker (sometimes hand-written)
- Exam next Thursday: bring 1(-sided) 8.5X11" sheet of notes
  - practice exam available today
- Course website: www.pa.msu.edu/~huston/phy294h/index.html
  - lectures will be posted frequently, mostly every day if I can remember to do so

Current

- Let me define the electric current I
  - $\vec{I}$ = dQ/dt (in the direction of the E field)
  - note that this is not the direction that the electrons move, but that's the convention we have
  - all of the effects that we are interested in are the same whether electrons move to the left or (fictitious) positive charges move to the right
  - unit of charge is the Coulomb (C)
  - unit of current is C/S or A (Ampere)
  - 1 A = 1 C/s



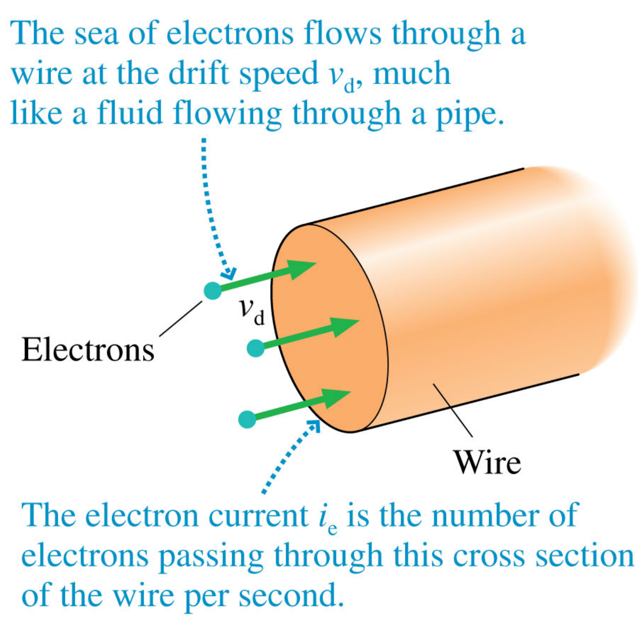
Another dead guy

- Andre Ampere (1775-1836)
- We' ll revisit him when we study the relationship between electric current and the magnetic field

Electron current

- We define the **electron current** i_e to be the number of electrons per second that pass through a cross section of the conductor.
- The number N_e of electrons that pass through the cross section during the time interval Δt is

$$N_e = i_e \Delta t$$



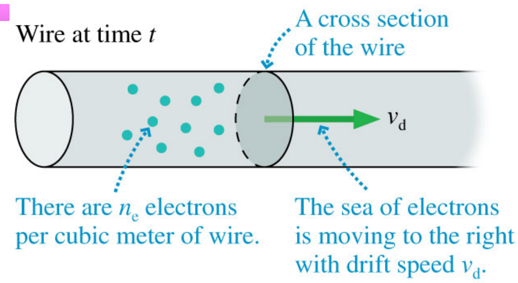
Electron current

- If the number density of conduction electrons is n_e, then the total number of electrons in the shaded cylinder is

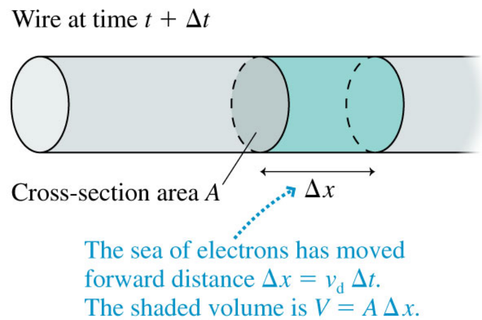
$$N_e = n_e V = n_e A\Delta x = n_e A v_d \Delta t$$

- So the electron current is:

$$i_e = n_e A v_d$$

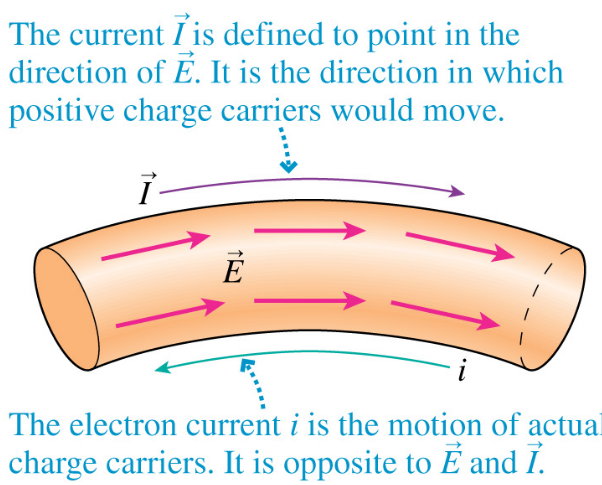


v_d is very small, fractions of a mm/s



Current

- $I = \Delta Q/\Delta t = eN_e/\Delta t = ei$
  - where we defined i as the electron current
  - each electron carries a charge e, so the current is the rate at which electrons move times the charge that each one carries
  - as Andre Ampere would say, eh voila!
- Define current density J
  - $J = I/A = nev_d$



iclicker question

A wire carries a current. If both the wire diameter and the electron drift speed are doubled, the electron current increases by a factor of

A. 2.
B. 4.
C. 6.
D. 8.
E. Some other value.

A wire carries a current. If both the wire diameter and the electron drift speed are doubled, the electron current increases by a factor of

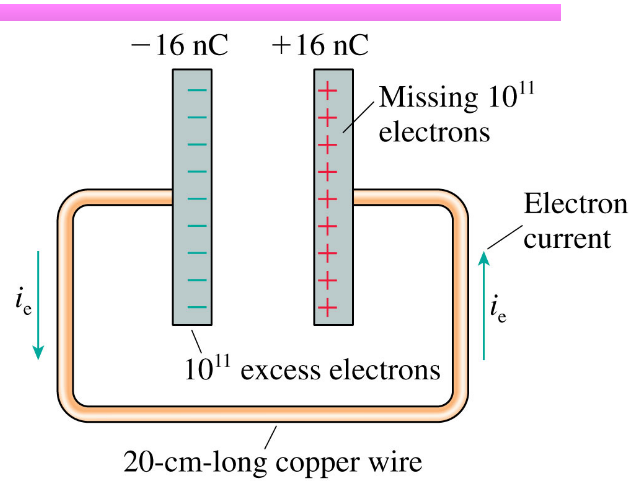
A. 2.
B. 4.
C. 6.
✔ **D. 8.** $i_e \propto A v_d$
E. Some other value.

- In most metals, each atom contributes one valence electron to the sea of electrons.
- Thus the number of conduction electrons n_e is the same as the number of atoms per cubic meter.

TABLE 30.1 Conduction-electron density in metals

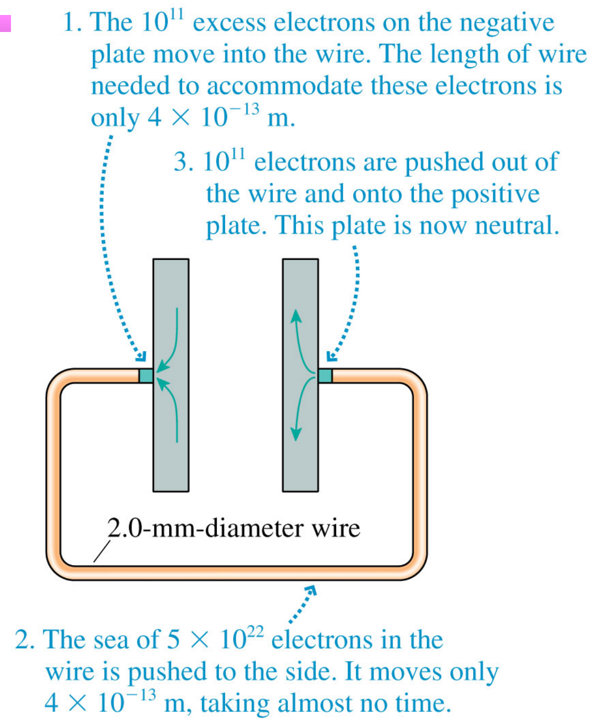
Metal	Electron density (m^{-3})
Aluminum	6.0×10^{28}
Copper	8.5×10^{28}
Iron	8.5×10^{28}
Gold	5.9×10^{28}
Silver	5.8×10^{28}

- How long should it take to discharge this capacitor?
- A typical drift speed of electron current through a wire is $v_d \approx 10^{-4}$ m/s.
- At this rate, it would take an electron about 2000 s (over half an hour) to travel 20 cm.



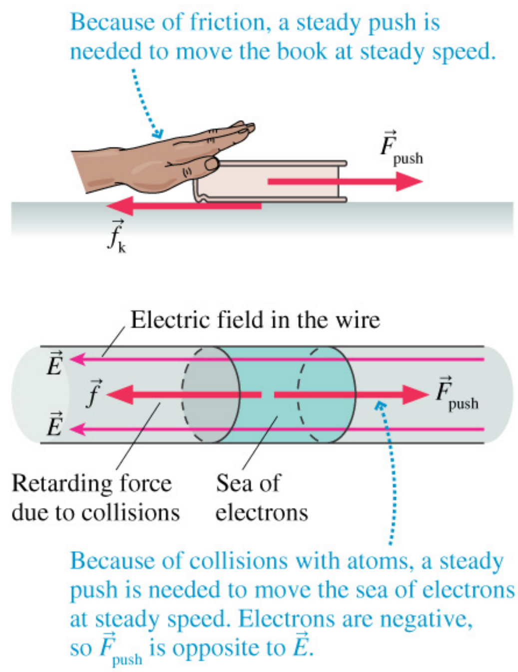
- But real capacitors discharge almost instantaneously!
- What's wrong with our calculation?

- The wire is *already full* of electrons!
- We don't have to wait for electrons to move all the way through the wire from one plate to another.
- We just need to slightly rearrange the charges on the plates *and* in the wire.



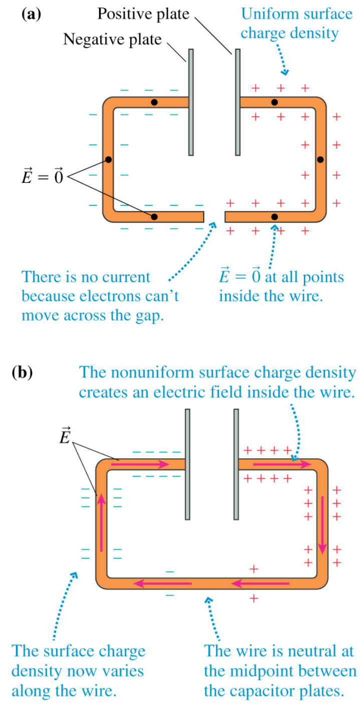
Pushing electrons

- As we discussed before, there needs to be an electric field created inside the wire in order for the electrons to have a net velocity in a particular direction



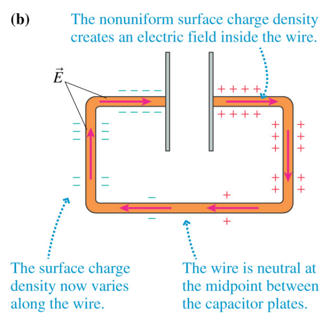
Let's go back to our two charged plates

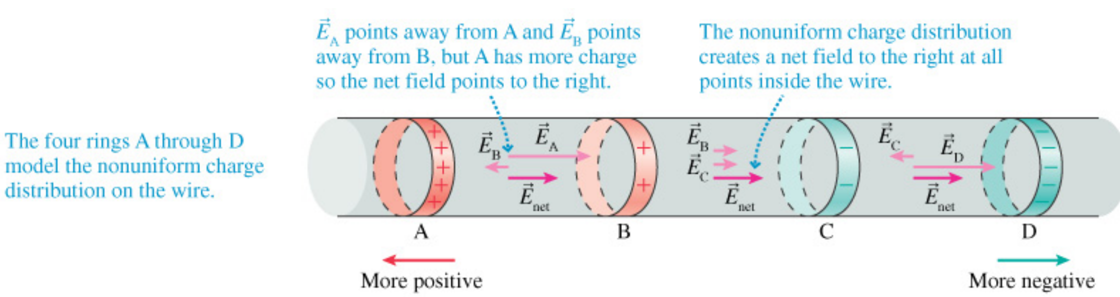
- With no connection in the middle, the charges distribute themselves over the surface of every conductor (the wires and the plates)
  - remember no excess electrons in the interior of a conductor in equilibrium situations
- If I suddenly connect the two ends of the wires, then the electrons near the negative (previously) end move onto the positive (previously) end
- Now there's a non-uniform distribution of charge and a non-equilibrium situation
  - not static so electrons throughout the conductor



Electric field

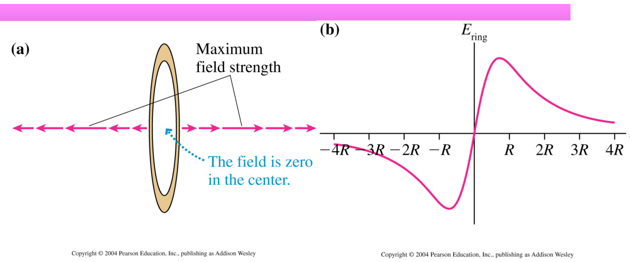
- Think about what's happening right after I connect the two wire ends
- Just consider 4 separate rings of the wire

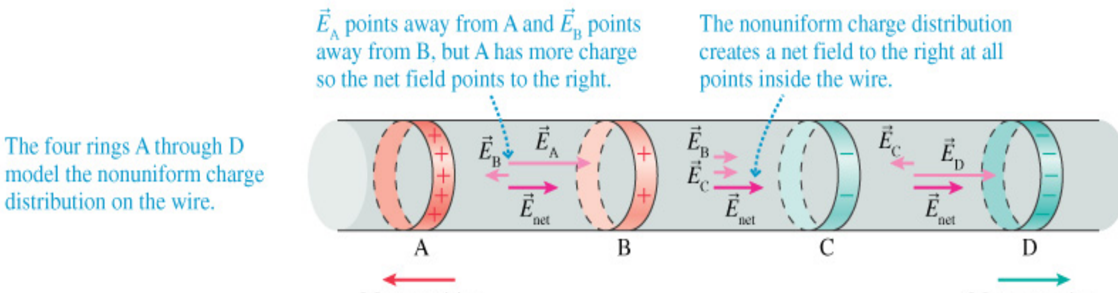




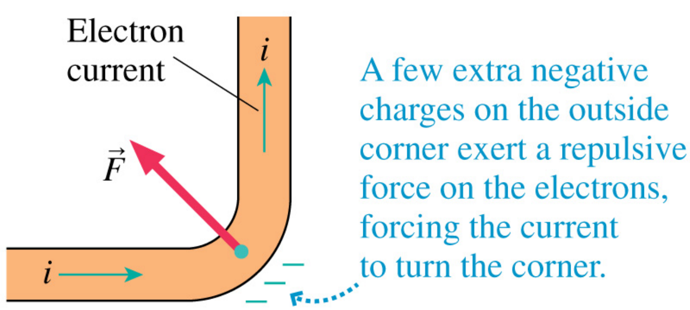
Electric field

- We know the electric field from a ring of charge
- Each ring of charge contributes
- Because of the gradient, there's a net electric field going from the more positive end towards the more negative end





- This model even explains electrons turning corners



Microscopic model of conduction

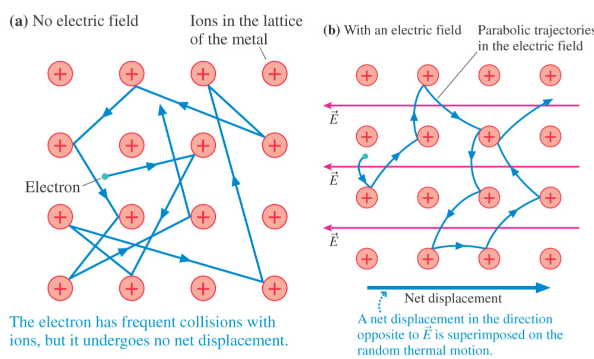
- Electrons are travelling at about 10^5 m/s
- Can think of them as behaving like gas molecules, travelling in straight lines between collisions
  - free electron or Drude model
  - doesn't take into account some quantum mechanical effects but good enough for the moment
- After an electric field is applied, the electrons are now following parabolic paths

For a gas of electrons, we can write

$v_{av} = [3kT/m]^{0.5}$

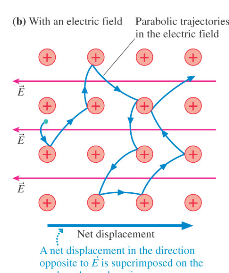
$v_{av} = [3(1.38X10^{-23}\ J/K)(293\ K)/9.1X10^{-31}\ kg)]^{1/2}$

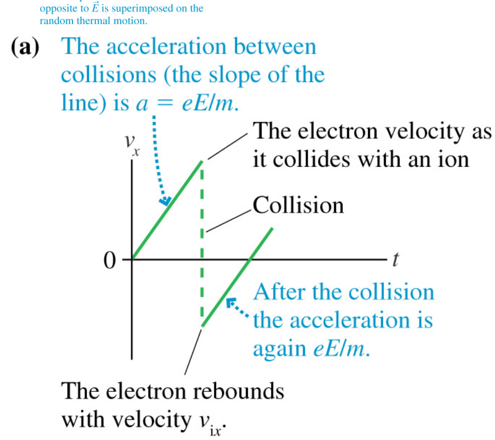
$v_{av} = 1.2\ X\ 10^5$ m/s



Microscopic model of conduction

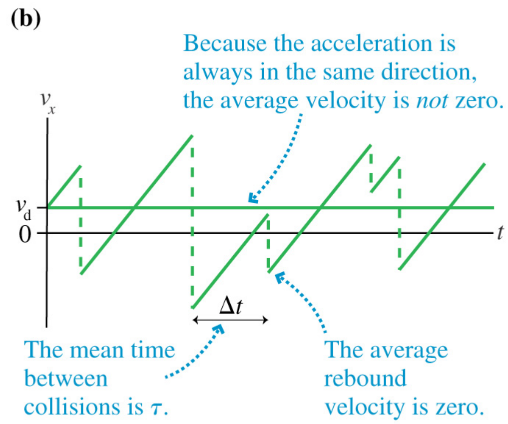
- Because of the electric field, the electron is going to experience an acceleration (between collisions) and the velocity in the direction of the electric field will look like
  - $v_x = v_{ix} - eE/m \cdot \Delta t$
  - acceleration is opposite the direction of the E field





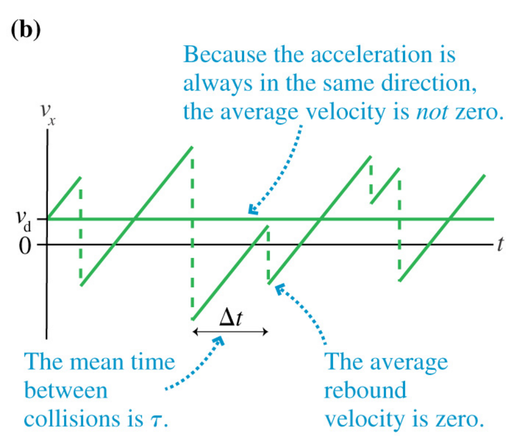
Mean time between collisions

- Let the average time between collisions be τ
- Then we can write
  - $v_D = -eE\tau/m$
  - after collisions v_{ix} ~0 so ignore first term
- But remember i(electron current) = nAv_d
  - so $|i| = (ne\tau A/m) \cdot E$
  - the electron current is proportional to the strength of the electric field
  - important result that we will re-visit



…or equivalently

- Or equivalently can think of the collisions as being a drag force acting on the electrons
  - ma = -eE - (a constant)v
  - looking at units the constant must have units of mass/time
  - $ma = -eE - m/\tau\ v$
  - when v reaches terminal speed (v_d), a = 0
  - $v_d = -eE\tau/m$



Conductivity and resistivity

- Define the conductivity of a material

$$\sigma = \text{conductivity} = \frac{n_e e^2 \tau}{m}$$

- The conductivity of a material characterizes the material as whole
- The current density J is related to the conductivity and the electric field by

$$J = \sigma E$$

- Can define the resistivity as the reciprocal of the conductivity->how difficult is it for the electrons to move

$$\rho = \text{resistivity} = \frac{1}{\sigma} = \frac{m}{n_e e^2 \tau}$$

Conductivity and resistivity

TABLE 30.2 Resistivity and conductivity of conducting materials

Material	Resistivity (Ω m)	Conductivity (Ω^{-1} m^{-1})
Aluminum	2.8×10^{-8}	3.5×10^{7}
Copper	1.7×10^{-8}	6.0×10^{7}
Gold	2.4×10^{-8}	4.1×10^{7}
Iron	9.7×10^{-8}	1.0×10^{7}
Silver	1.6×10^{-8}	6.2×10^{7}
Tungsten	5.6×10^{-8}	1.8×10^{7}
Nichrome*	1.5×10^{-6}	6.7×10^{5}
Carbon	3.5×10^{-5}	2.9×10^{4}

*Nickel-chromium alloy used for heating wires.