# PHY294H

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- Homework will be with Mastering Physics (and an average of 1 handwritten problem per week)
  - Problem 29.77 (already assigned) will be the hand-in problem for 4<sup>th</sup> 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
  - T = 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

Surface charges have created an electric field inside the wire.





The current  $\vec{l}$  is the rate at which the electric field seems to push *positive* charge through the wire.  $\vec{l}$  is in the direction of  $\vec{E}$ .

## 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<sub>e</sub> to be the number of electrons per second that pass through a cross section of the conductor.
- The number N<sub>e</sub> of electrons that pass through the cross section during the time interval Δt is

$$N_{\rm e} = i_{\rm e} \Delta t$$

The sea of electrons flows through a wire at the drift speed  $v_d$ , much like a fluid flowing through a pipe.



The electron current  $i_e$  is the number of electrons passing through this cross section of the wire per second.

#### Electron current

 If the number density of conduction electrons is n<sub>e</sub>, then the total number of electrons in the shaded cylinder is

$$N_{\rm e} = n_{\rm e} V$$
$$= n_{\rm e} A \Delta x$$
$$= n_{\rm e} A v_{\rm d} \Delta t$$

So the electron current is:

$$i_{\rm e} = n_{\rm e} A v_{\rm d}$$



## Current

- $I = \Delta Q / \Delta t = e N_e / \Delta t = e i$ 
  - 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<sub>d</sub>

The current  $\vec{I}$  is defined to point in the direction of  $\vec{E}$ . It is the direction in which positive charge carriers would move.



The electron current *i* is the motion of actual charge carriers. It is opposite to  $\vec{E}$  and  $\vec{I}$ .

### 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.

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- B. 4.
- C. 6.



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<sub>e</sub> is the same as the number of atoms per cubic meter.

TABLE 30.1Conduction-electrondensity in metals

Metal	Electron density (m <sup>-3</sup> )
Aluminum	$6.0  imes 10^{28}$
Copper	$8.5  imes 10^{28}$
Iron	$8.5  imes 10^{28}$
Gold	$5.9  imes 10^{28}$
Silver	$5.8  imes 10^{28}$

- How long should it take to discharge this capacitor?
- A typical drift speed of electron current through a wire is v<sub>d</sub> ≈ 10<sup>-4</sup> 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.

1. The  $10^{11}$  excess electrons on the negative plate move into the wire. The length of wire needed to accommodate these electrons is only  $4 \times 10^{-13}$  m.



2. The sea of  $5 \times 10^{22}$  electrons in the wire is pushed to the side. It moves only  $4 \times 10^{-13}$  m, taking almost no time.

### **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







Because of collisions with atoms, a steady push is needed to move the sea of electrons at steady speed. Electrons are negative, so  $\vec{F}_{push}$  is opposite to  $\vec{E}$ .

#### 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

 $\vec{E}_{\rm A}$  points away from A and  $\vec{E}_{\rm B}$  points

away from B, but A has more charge



The nonuniform charge distribution

creates a net field to the right at all

The four rings A through D model the nonuniform charge distribution on the wire.



# **Electric field**

(b)  $E_{\rm ring}$ Maximum field strength (a) We know the electric field from a ring of charge Each ring of charge 4R - 3R - 2R - R $\overrightarrow{R}$ 2R 3R 4RThe field is zero contributes in the center. Because of the gradient, there's a net electric field going from the more positive end towards the more negative end  $\vec{E}_{\rm A}$  points away from A and  $\vec{E}_{\rm B}$  points The nonuniform charge distribution away from B, but A has more charge creates a net field to the right at all so the net field points to the right. points inside the wire.  $\vec{E}_{\rm B}$  $\vec{E}_{\rm C}$  $\vec{E}_{\rm D}$  $\vec{E}_{\rm B}$  $E_{\rm C}$ The four rings A through D model the nonuniform charge distribution on the wire.  $\vec{E}_{ne}$  $\vec{E}_{..}$ В D А

 This model even explains electrons turning corners



A few extra negative charges on the outside corner exert a repulsive force on the electrons, forcing the current to turn the corner.

...

#### Microscopic model of conduction

- Electrons are travelling at about 10<sup>5</sup> m/s
- Can think of them as behaving<sup>v</sup><sub>a</sub> 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  $v_{av} = [3kT/m]^{0.5}$
- Can think of them as behaving  $V_{av} = [3(1.38 \times 10^{-23} \text{ J/K})(293 \text{ K})/9.1 \times 10^{-31} \text{ kg})]^{1/2}$

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



#### 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
  - $v_x = v_{ix} eE/m \Delta t$
  - acceleration is opposite the direction of the E field



with velocity  $v_{ix}$ .

#### Mean time between collisions

- Let the average time between collisions be τ
- Then we can write
  - $v_D = -eE\tau/m$
  - after collisions v<sub>ix</sub> ~0 so ignore first term
- But remember i(electron current) = nAv<sub>d</sub>
  - so |i| = (neτA/m)·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/τ v
  - when v reaches terminal speed (v<sub>d</sub>), a = 0
  - $v_d = -eE\tau/m$



## Conductivity and resistivity

• Define the conductivity of a material

$$\sigma = \text{conductivity} = \frac{n_{\rm e}e^2\pi}{m}$$

- 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

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

### Conductivity and resistivity

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

 TABLE 30.2
 Resistivity and conductivity of conducting materials

\*Nickel-chromium alloy used for heating wires.