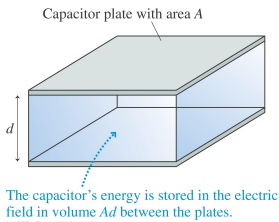


# The Energy in the Electric Field



- Where is the energy in a capacitor actually stored? Where is the “spring” we are stretching?
- The energy is in the field itself! Maybe this field isn't just some abstract idea after all.

- The energy stored in a capacitor is

$$U_C = \frac{C(\Delta V)^2}{2} = \frac{1}{2} \frac{\epsilon_0 A}{d} (Ed)^2 = \frac{\epsilon_0}{2} (Ad) E^2$$

- In fact, let's define the energy density in the capacitor

$$u_E = \frac{\text{energy stored}}{\text{volume}} = \frac{U_C}{Ad} = \frac{\epsilon_0}{2} E^2$$

# The Energy in the Electric Field

## Example 30.10

The plates of a parallel-plate capacitor are separated by 1.0mm. What is the energy density in the capacitor's electric field if the capacitor is charged to 500V?

- The electric field is

$$E = \frac{\Delta V_C}{d} = \frac{500 \text{ V}}{0.0010 \text{ m}} = 5.0 \times 10^5 \text{ V/m}$$

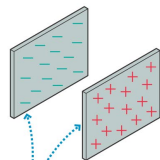
- The energy density is then

$$u_E = \frac{\epsilon_0}{2} E^2 = \frac{(8.85 \times 10^{-12} \text{ C}^2 / \text{Nm}^2)(5.0 \times 10^5 \text{ V/m})^2}{2} = 1.1 \text{ J/m}^3$$

# Current and Resistance (Chapter 31)

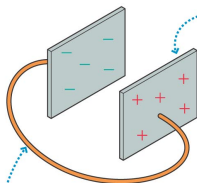
- Until now we have been talking about **electrostatics**. Now we turn to moving charges—**current** and **resistance**.
- What causes charges to flow through a wire? What determines the properties of the flow?
- We will need to understand this at both the macroscopic and microscopic levels.
- All that stuff we have been learning about electric field was not just a waste of time...

# The Electron Current (31.1)



Isolated electrodes stay charged indefinitely.

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However, a connecting wire quickly discharges the capacitor.

The net charge of each plate is decreasing.

- If we connect the two charged plates of a capacitor with a conducting wire they are quickly **discharged**
- It would seem that charges flow through the wire until the two plates are at the same potential. We would like to know. . .
  - What is it that moves through the wire?
  - What makes it move?
  - How fast does it move?
  - What controls its motion?

# Charge Carriers

- So, what happens when a capacitor discharges? What is moving? Are positive charges moving or negative?
- Of course, it is the electrons that are moving. But how do we know?
- A very neat experiment was performed by Tolman and Stewart in 1916. Imagine the electrons are “fluid” and throw a metal rod. See what charge the “back-end” picks up....it is negative!

When a metal bar accelerates to the right, inertia causes the charge carriers to be displaced to the rear surface. The front surface becomes oppositely charged.



Sea of positive charge carriers

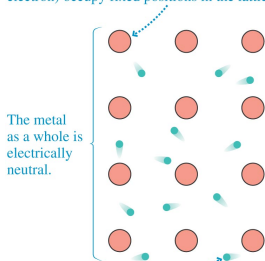


Sea of negative charge carriers

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# Charge Carriers

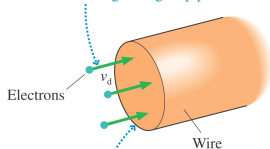
Ions (the metal atoms minus one valence electron) occupy fixed positions in the lattice.



The conduction electrons (one per atom) are free to move around. They are bound to the solid as a whole, not to any particular atom.

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

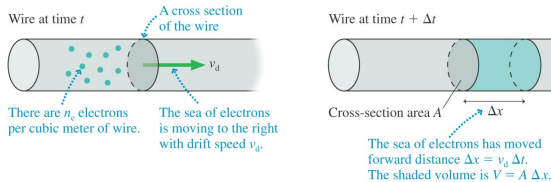


The electron current  $i_e$  is the number of electrons passing through this cross section

- In a metal each atom has a conduction electron which is free to move around, generally at random.
- However, we can push the entire sea of electrons in one direction using an electric field (liquid through a pipe).
- This net motion occurs at the **drift speed**  $v_d$ . A typical value is  $v_d = 10^{-4}\text{m/s}$ .
- If you push the electrons and count the number that pass per second you can define the **electron current** as

$$i_e = \frac{N_e}{\Delta t}$$

# Charge Carriers



- The figure above shows the sea of electrons moving to the right a distance  $\Delta x$  in time  $\Delta t$ .
- The electrons travel  $\Delta x = v_d \Delta t$  to the right, forming a cylinder of volume  $V = A \Delta x$ . The number of electrons in the cylinder is

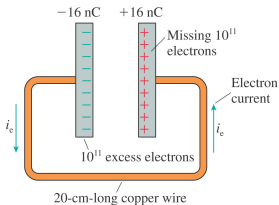
$$N_e = n_e V = n_e A \Delta x = n_e A v_d \Delta t$$

- The electron current in the wire is then

$$i_e = n_e A v_d$$

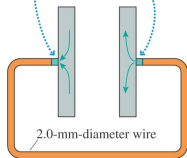
increase the current by increasing the electron density, the area of the “pipe” or the drift velocity.

# Discharging a Capacitor



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  $4 \times 10^{-13} \text{ m}$ .

3.  $10^{11}$  electrons are pushed out of the wire and onto the positive plate. This plate is now neutral.

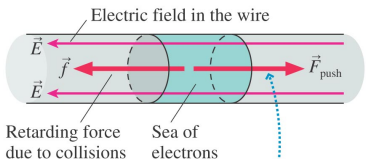
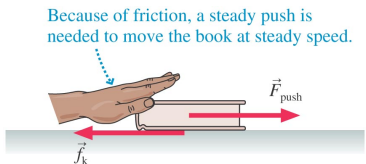


2. The sea of  $5 \times 10^{22}$  electrons in the wire is pushed to the side. It moves only  $4 \times 10^{-13} \text{ m}$ , taking almost no time.

- That drift velocity is pretty slow. It would take a long time to turn on a light if electricity flowed from the switch to the bulb at  $10^{-4} \text{ m/s}$ !
- The conducting wire is already full of electrons. Pushing on the sea makes electrons pop-off the end.
- Estimate that there are  $5 \times 10^{22}$  conduction electrons in a copper wire. The negative plate has only  $10^{11}$  excess electrons.
- The length of copper wire which holds  $10^{11}$  electrons is only  $4 \times 10^{-13} \text{ m}$ ...which only takes 4ns to cross at  $v_d$ .



# Creating a Current (31.2)

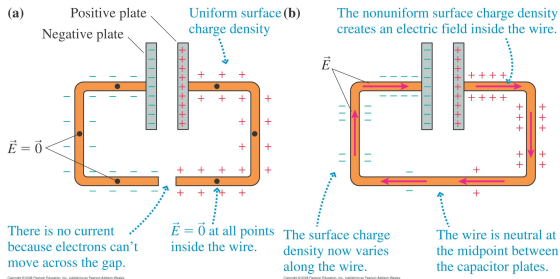


Because of collisions with atoms, a steady push is needed to move the sea of electrons at steady speed. Electrons are negative, so  $\vec{F}_{\text{push}}$  is opposite to  $\vec{E}$ .

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- If you push a book across a table you need to keep pushing or it will stop (and heat up) due to friction.
- If you want to move a current through a wire you must also keep pushing. The electrons will bounce off of atoms and change direction (and heat up the wire).
- To push the electrons you need to set up an electric field in the conductor.  
**An electron current is a non-equilibrium motion of charges sustained by an internal electric field.**

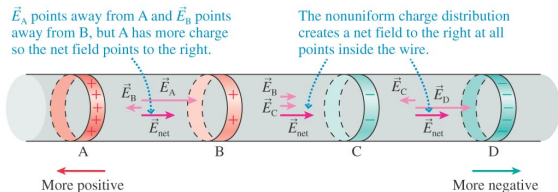
# Establishing the Electric Field in a Wire



- The situation on the left is electrostatic equilibrium. Excess charge is shared throughout each conductor, no charges are in motion.
- On the right is a picture just after connection. Positive flow into the negative side has begun but there is still a non-uniform distribution.
- The non-uniform distribution creates an internal electric field...which sustains a current.

# Establishing the Electric Field in a Wire

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



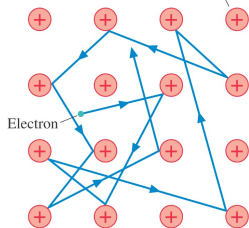
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- We have studied a ring of charge already a couple of times. You know the effect on the axis of the ring.
- Excess charges in the conductor are all on the outside—a ring of charge!
- These rings are not equally charged in a non-uniform distribution. So, an electric field is created inside the wire.
- The electric field drives charges inside the wire.

# A Model of Conduction

(a) No electric field

Ions in the lattice of the metal

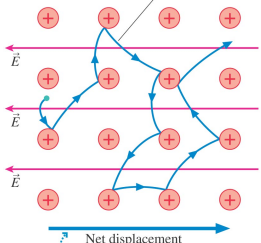


The electron has frequent collisions with ions, but it undergoes no net displacement.

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(b) With an electric field

Parabolic trajectories in the electric field



A net displacement in the direction

- We can understand conduction on a microscopic scale by treating conducting electrons as free particles (like molecules in a gas).
- They bounce around randomly and are moving very fast throughout the crystal lattice of the metal.
- They bounce off of atoms at random and have average velocity zero.
- If we apply an electric force the electrons follow a series of parabolic trajectories.
- There is a net movement to the right, but it is small compared to the random motion.