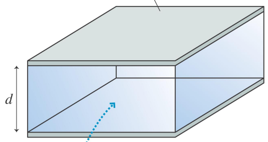
The Energy in the Electric Field



The capacitor's energy is stored in the electric field in volume Ad between the plates.

- 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

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

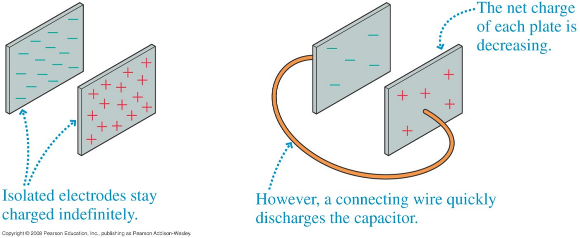
- The energy density is then

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

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...

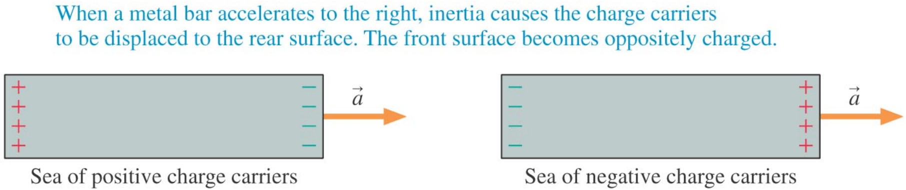
The Electron Current (31.1)



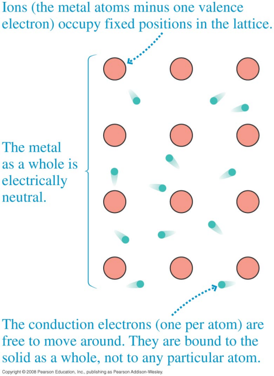
- If we connect the two charged plates of a capacitor with a conducting wire they are quickly discharged
- It would seem that charges flow through the wire until the two plates are at the same potential. We would like to know…
  - What is it that moves through the wire?
  - What makes it move?
  - How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

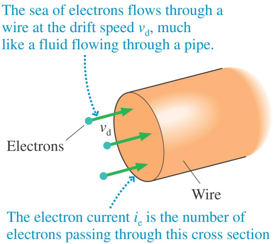
Charge Carriers

- 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!



Charge Carriers

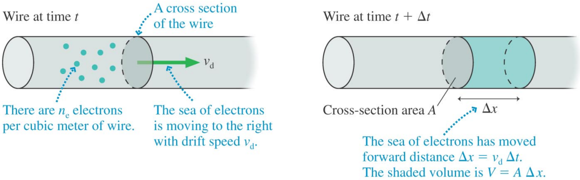




- In a metal each atom has a conduction electron which is free to move around, generally at random.
- However, we can push the entire sea of electrons in one direction using an electric field (liquid through a pipe).
- This net motion occurs at the drift speed v_d. A typical value is $v_d = 10^{-4}$m/s.
- 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 Δx in time Δt.
- 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

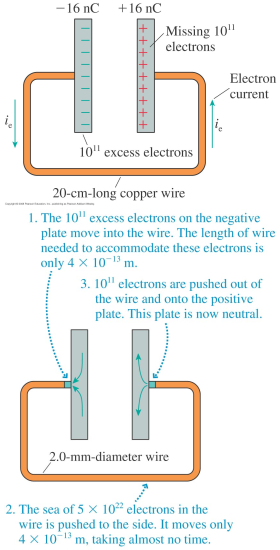
$$N_e = n_e V = n_e A \Delta x = n_e A v_d \Delta t$$

- The electron current in the wire is then

$$i_e = n_e A v_d$$

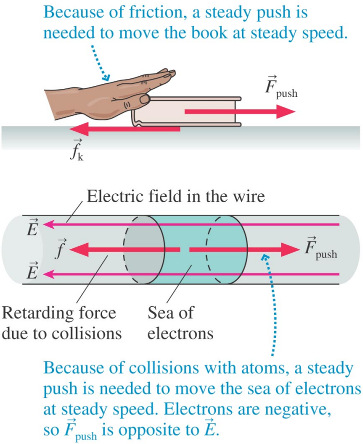
increase the current by increasing the electron density, the area of the “pipe” or the drift velocity.

Discharging a Capacitor



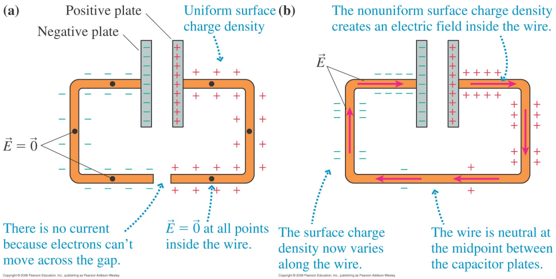
- That drift velocity is pretty slow. It would take a long time to turn on a light if electricity flowed from the switch to the bulb at 10^{-4}m/s!
- The conducting wire is already full of electrons. Pushing on the sea makes electrons pop-off the end.
- Estimate that there are 5×10^{22} conduction electrons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

Creating a Current (31.2)



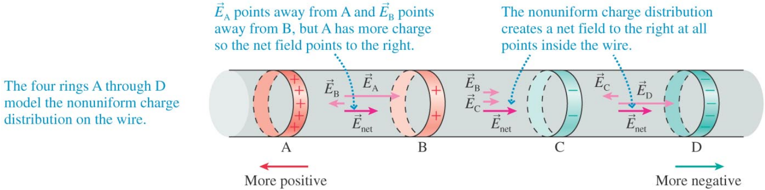
- If you push a book across a table you need to keep pushing or it will stop (and heat up) due to friction.
- If you want to move a current through a wire you must also keep pushing. The electrons will bounce off of atoms and change direction (and heat up the wire).
- To push the electrons you need to 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



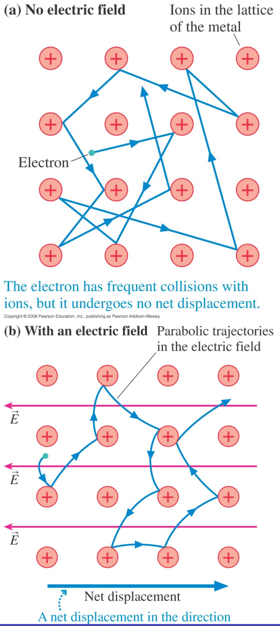
- The situation on the left is electrostatic equilibrium. Excess charge is shared throughout each conductor, no charges are in motion.
- On the right is a picture just after connection. Positive flow into the negative side has begun but there is still a non-uniform distribution.
- The non-uniform distribution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

Establishing the Electric Field in a Wire



- 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



- 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.