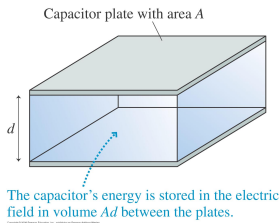
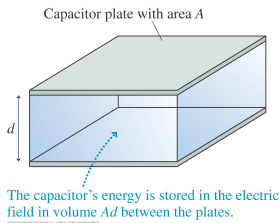


The Energy in the Electric Field



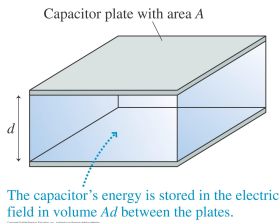
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The Energy in the Electric Field



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The Energy in the Electric Field

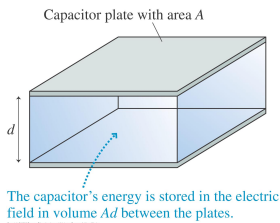


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$$U_C = \frac{C(\Delta V)^2}{2} = \frac{1}{2} \frac{\epsilon_0 A}{d} (Ed)^2 = \frac{\epsilon_0}{2} (Ad) E^2$$

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- 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

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

The Energy in the Electric Field

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

- The energy density is then

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

Current and Resistance (Chapter 31)

- Until now we have been talking about **electrostatics**. Now we turn to moving charges - **current** and **resistance**.

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- What causes charges to flow through a wire? What determines the properties of the flow?

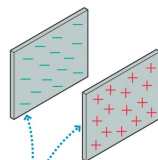
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Current and Resistance (Chapter 31)

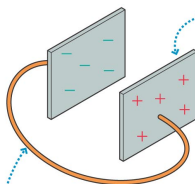
- Until now we have been talking about **electrostatics**. Now we turn to moving charges - **current** and **resistance**.
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- We will need to understand this at both the macroscopic and microscopic levels.
- All that stuff we have been learning about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

The Electron Current (31.1)



Isolated electrodes stay charged indefinitely.

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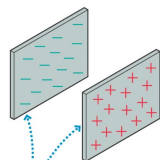


However, a connecting wire quickly discharges the capacitor.

The net charge of each plate is decreasing.

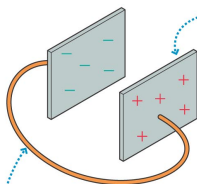
- If we connect the two charged plates of a capacitor with a conducting wire they are quickly **discharged**

The Electron Current (31.1)



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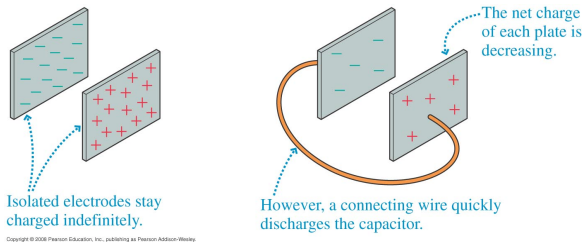


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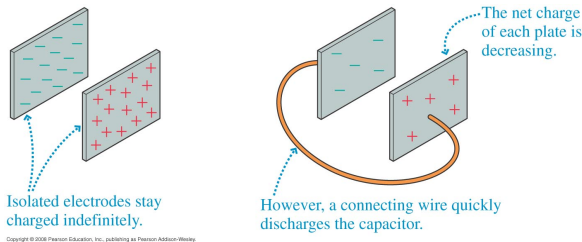
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- It would seem that charges flow through the wire until the two plates are at the same potential. We would like to know

The Electron Current (31.1)



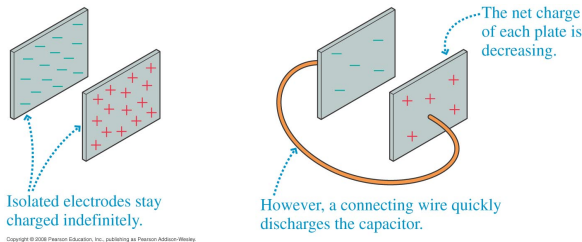
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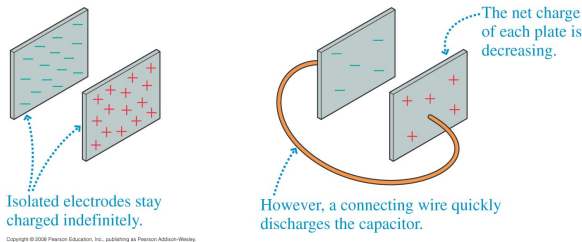
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- It would seem that charges flow through the wire until the two plates are at the same potential. We would like to know
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 - What makes it move?
 - How fast does it move?
 - What controls its motion?

Charge Carriers

- So, what happens when a capacitor discharges? What is moving? Are positive charges moving or negative?

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

- So, what happens when a capacitor discharges? What is moving? Are positive charges moving or negative?
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Sea of negative charge carriers

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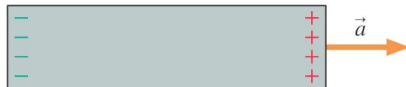
Charge Carriers

- 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

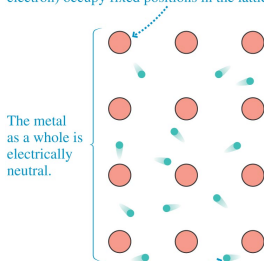


Sea of negative charge carriers

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Charge Carriers

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

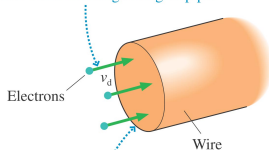


- In a metal each atom has a conduction electron which is free to move around, generally at random.

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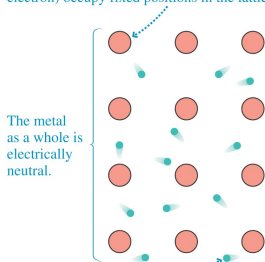
The sea of electrons flows through a wire at the drift speed v_d , much like a fluid flowing through a pipe.



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

Charge Carriers

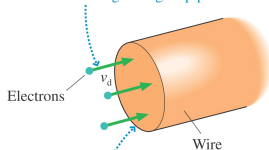
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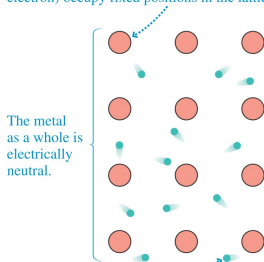


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Charge Carriers

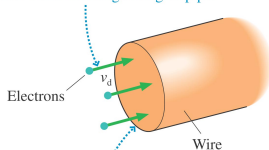
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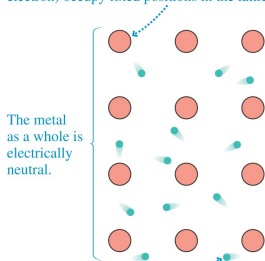


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Charge Carriers

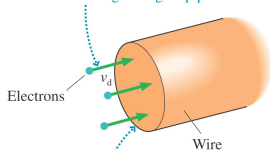
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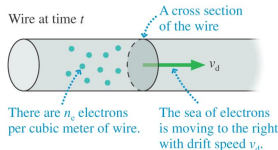


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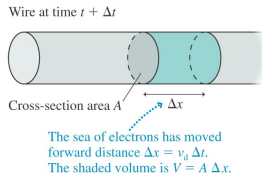
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- However, we can push the entire sea of electrons in one direction using an electric field (liquid through a pipe).
- This net motion occurs at the **drift speed** v_d . A typical value is $v_d = 10^{-4} \text{ m/s}$.
- If you push the electrons and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

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

Charge Carriers

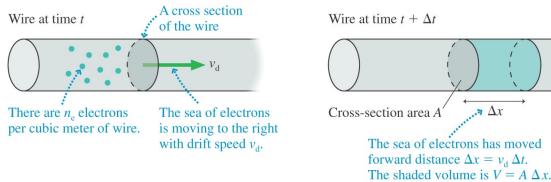


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- The figure above shows the sea of electrons moving to the right a distance Δx in time Δt .

Charge Carriers

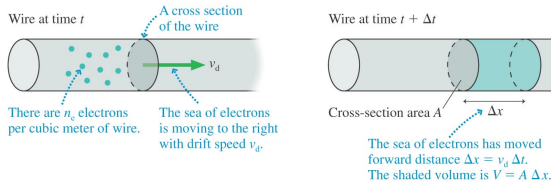


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- The electrons travel $\Delta x = v_d \Delta t$ to the right, forming a cylinder of volume $V = A \Delta x$. The number of electrons in the cylinder is

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

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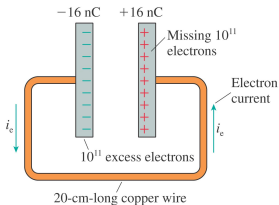
$$N_e = n_e V = n_e A \Delta x = n_e A v_d \Delta t$$

- 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.

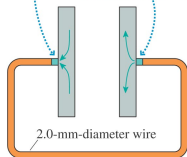
Discharging a Capacitor



- 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 !

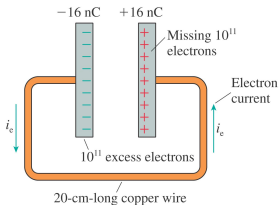
1. The 10^{11} excess electrons on the negative plate move into the wire. The length of wire needed to accommodate these electrons is only $4 \times 10^{-13}\text{ m}$.

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



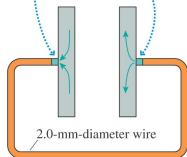
2. The sea of 5×10^{22} electrons in the wire is pushed to the side. It moves only $4 \times 10^{-13}\text{ m}$, taking almost no time.

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

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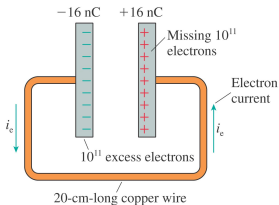


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- That drift velocity is pretty slow. It would take a long time to turn on a light if electricity flowed from the switch to the bulb at 10^{-4} m/s !
- The conducting wire is already full of electrons. Pushing on the sea makes electrons pop-off the end.

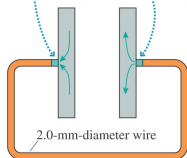
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Discharging a Capacitor



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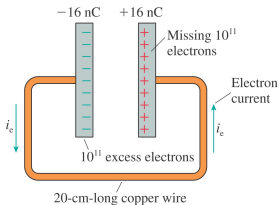
3. 10^{11} electrons are pushed out of the wire and onto the positive plate. This plate is now neutral.



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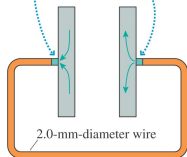
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- Estimate that there are 5×10^{22} conduction electrons in a copper wire. The negative plate has only 10^{11} excess electrons.

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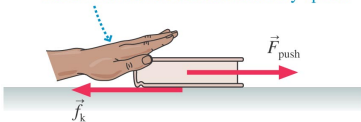


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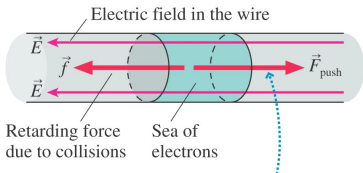
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- The length of copper wire which holds 10^{11} electrons is only $4 \times 10^{-13} \text{ m}$...which only takes 4ns to cross at v_d .

Creating a Current (31.2)

Because of friction, a steady push is needed to move the book at steady speed.



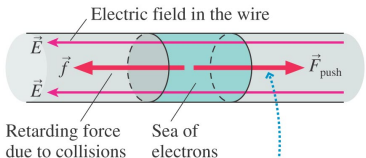
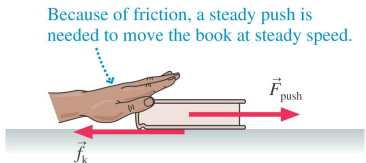
- If you push a book across a table you need to keep pushing or it will stop (and heat up) due to friction.



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} .

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Creating a Current (31.2)

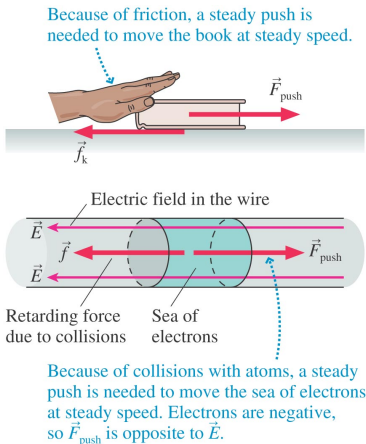


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- If you want to move a current through a wire you must also keep pushing. The electrons will bounce off of atoms and change direction (and heat up the wire).

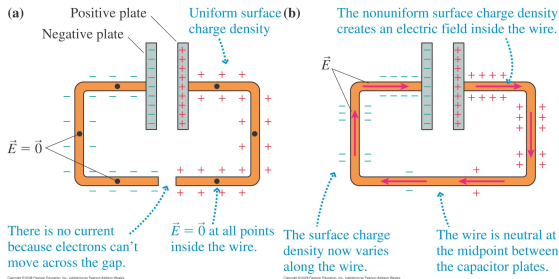
Creating a Current (31.2)



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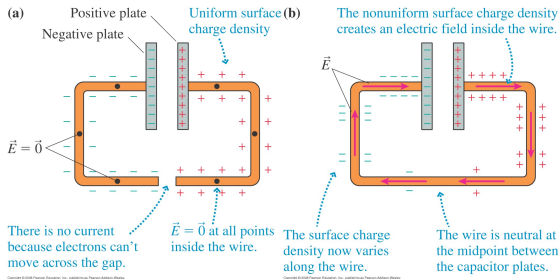
- If you push a book across a table you need to keep pushing or it will stop (and heat up) due to friction.
- If you want to move a current through a wire you must also keep pushing. The electrons will bounce off of atoms and change direction (and heat up the wire).
- To push the electrons you need to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



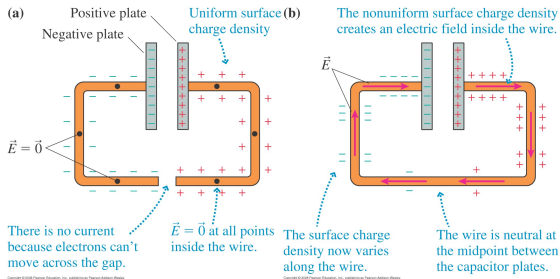
- The situation on the left is electrostatic equilibrium. Excess charge is shared throughout each conductor, no charges are in motion.

Establishing the Electric Field in a Wire



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- 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.

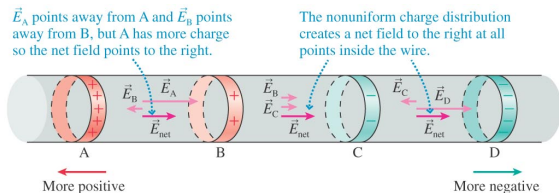
Establishing the Electric Field in a Wire



- 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.

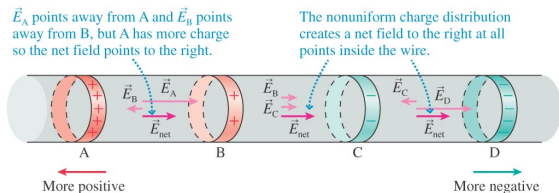


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- We have studied a ring of charge already a couple of times. You know the effect on the axis of the ring.

Establishing the Electric Field in a Wire

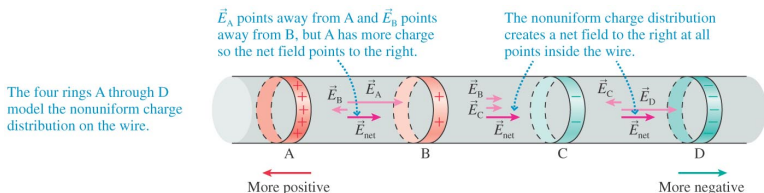
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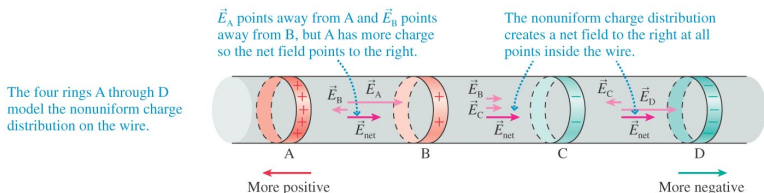
- We have studied a ring of charge already a couple of times. You know the effect on the axis of the ring.
- Excess charges in the conductor are all on the outside - a ring of charge!

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.

Establishing the Electric Field in a Wire

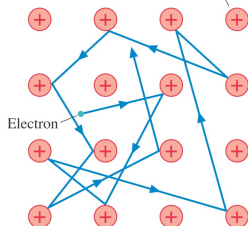


- We have studied a ring of charge already a couple of times. You know the effect on the axis of the ring.
- Excess charges in the conductor are all on the outside - a ring of charge!
- These rings are not equally charged in a non-uniform distribution. So, an electric field is created inside the wire.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

A Model of Conduction

(a) No electric field

Ions in the lattice of the metal

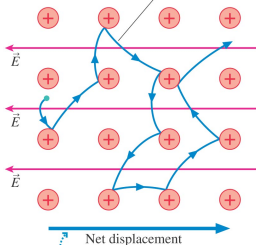


The electron has frequent collisions with ions, but it undergoes no net displacement.

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(b) With an electric field

Parabolic trajectories in the electric field

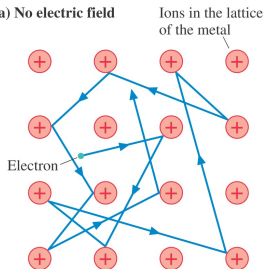


A net displacement in the direction

- We can understand conduction on a microscopic scale by treating conducting electrons as free particles (like molecules in a gas).

A Model of Conduction

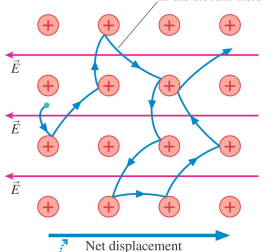
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(b) With an electric field



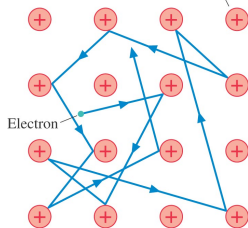
A net displacement in the direction

- 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.

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Ions in the lattice of the metal

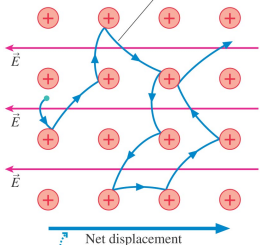


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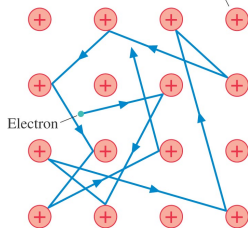
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- They bounce off of atoms at random and have average velocity zero.

A Model of Conduction

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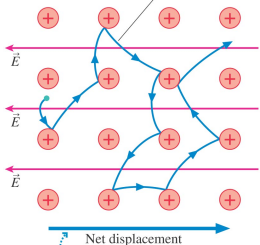


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A net displacement in the direction

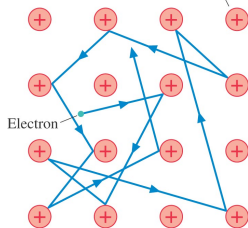
Neil Alberding (SFU Physics)

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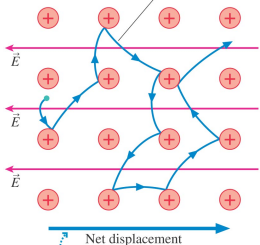


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Parabolic trajectories in the electric field



A net displacement in the direction

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- 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.