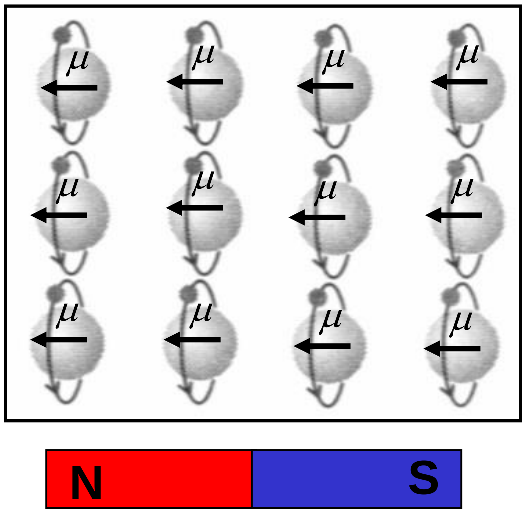
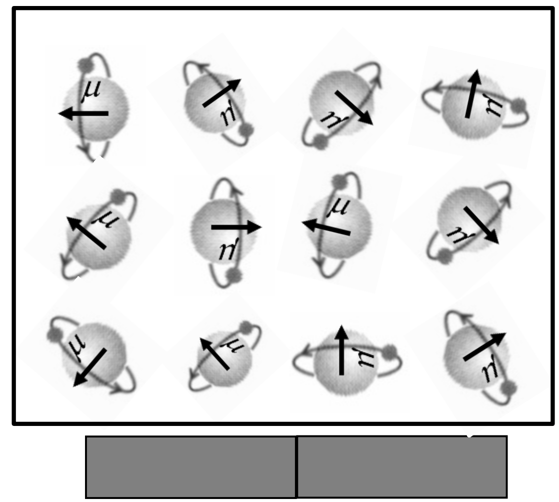
Last Time

- Magnetic Field of a Current Loop
- Magnetic Dipole Moment
- Atomic magnetic moment.
- Permanent Magnets

Permanent Magnets

Alignment of atomic dipole moments form domains in ferromagnets:





ferromagnetic materials:
Permanent magnetic moment
iron, cobalt, nickel.

Quantum Mechanics → strong short ranged electrical interaction between atoms → favors alignment of atomic magnetic moments

Most materials only magnetize in the presence of an external magnetic field

$\vec{M}$ along $\vec{B}_{ext} \rightarrow$ Paramagnetic $\rightarrow$ Atraction

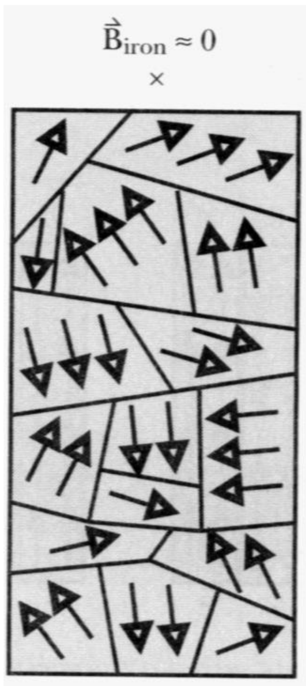
(Most atoms with incomplete orbitals)

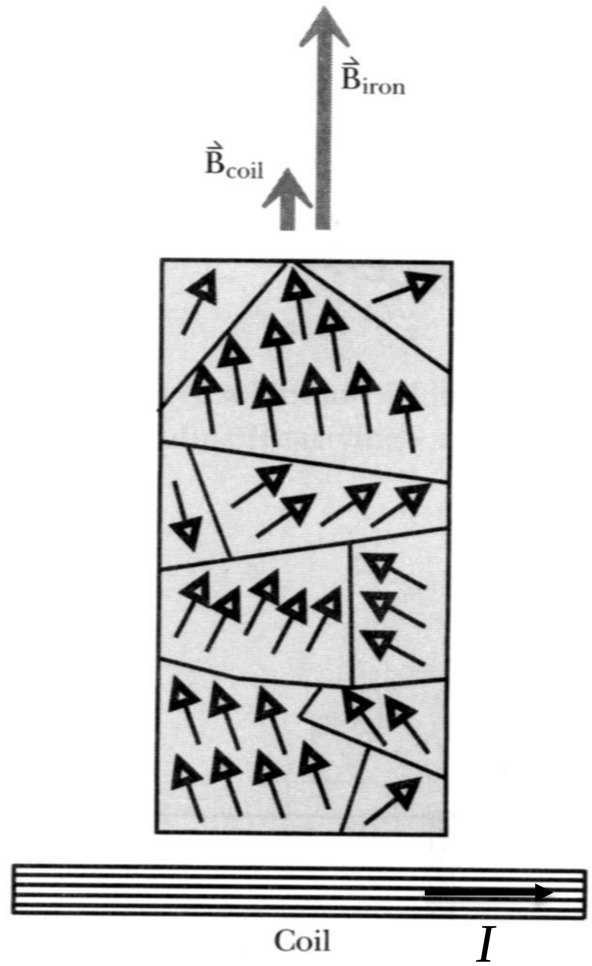
$\vec{M}$ opposite $\vec{B}_{ext} \rightarrow$ Diamagnetic $\rightarrow$ Repulsion

(water, wood, organic compounds)

Reality Physics - Domains

Ferromagnetic materials
have magnetic domains!



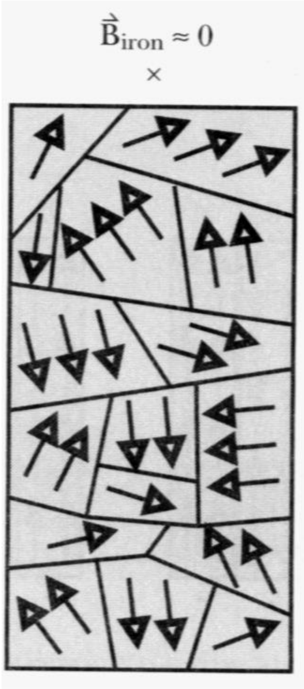


Apply
B-Field
to Align
Domains

Heating a ferromagnet will demagnetize it.

Why are there Multiple Domains?

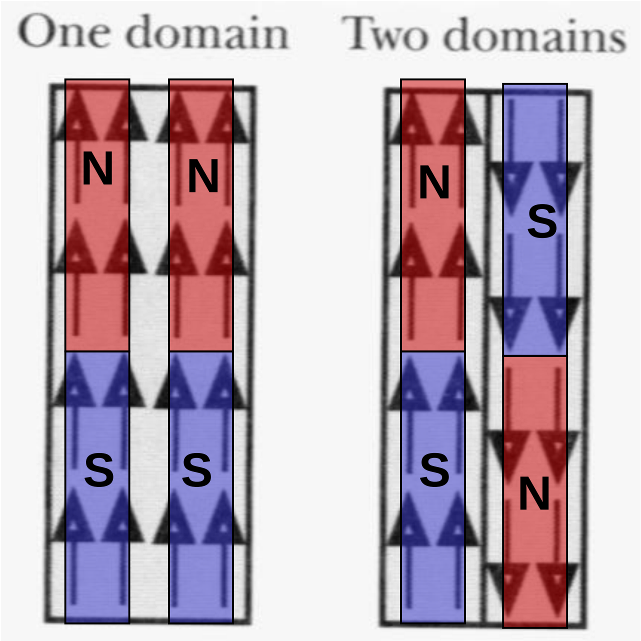
Magnetic domains



Net magnetic field energy cost of large domain is high, so the magnetic field from one domain tends to anti-align the next domain (long range weak magnetic interaction)

VS

Neighboring atoms try to align their magnetic moments (strong short-range electric interaction)



Which one prevails depends on the geometry

Today

- Equilibrium *vs*. Steady State in a Circuit
- What is "used up" in a circuit?
- Kirchhoff's Current Node Law
- **E**-field inside a wire

Key Ideas in Chapter 18: Electric Circuits

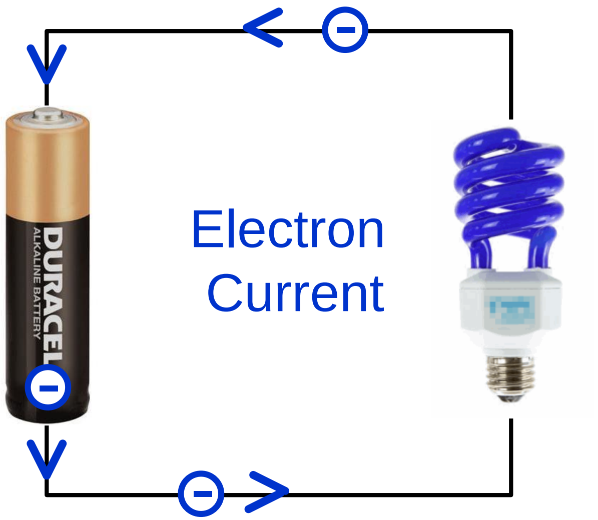
- **Surface charges on the wires make the electric field that drives the current in a circuit.**
  - Transient effects precede the steady state.
  - A battery maintains a charge separation and a potential difference.
- **How to analyze circuits:**
  - Current-node rule: Current into a node equals current out of the node.
  - Voltage-loop rule: The total potential difference around a loop is zero.

We want to find out:

Microscopic Questions:

- Are charges used up in a circuit?
- Exactly how does a current-carrying wire create and maintain nonzero Efield inside?
- What does the battery do?

Conventional Current and Electron Current



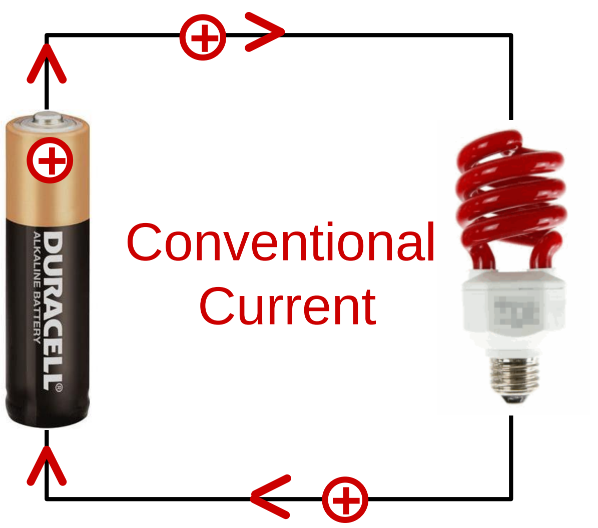
<u>Electron Current:</u>

Electrons exit battery at (**-**) terminal, and enter battery at (**+**) terminal

$$i = nA\bar{v} \quad \text{where} \quad n = \text{density of mobile electrons}$$

$$A = \text{cross-sectional area}$$

$$\bar{v} = \text{drift speed}$$



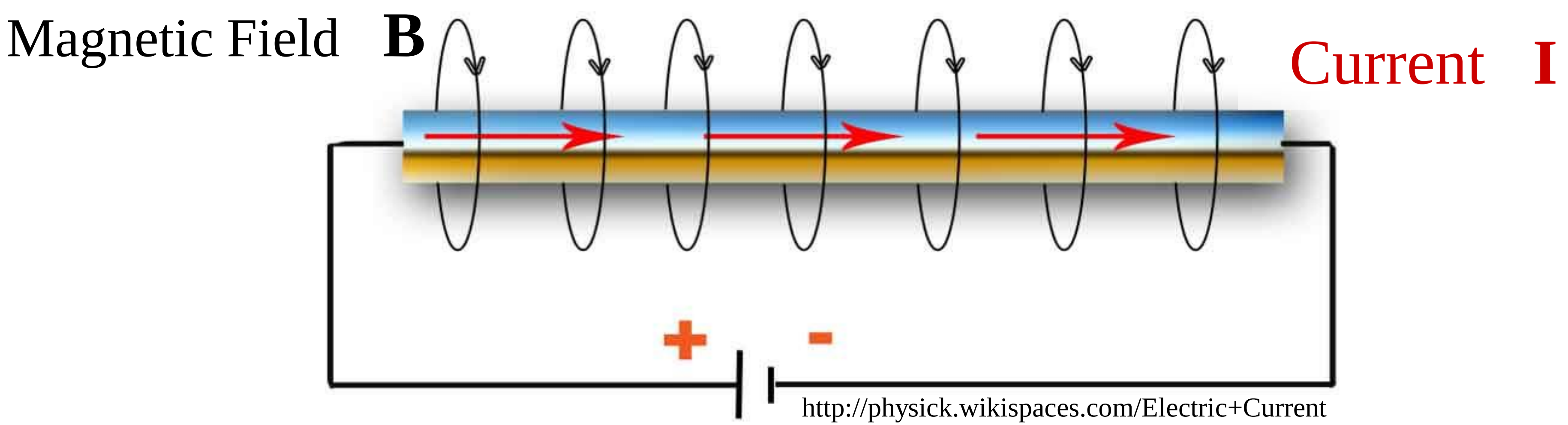
<u>Conventional Current:</u>

Positive charges exit battery at (**+**) terminal, and enter battery at (**-**) terminal

$$I = |q|\, nA\bar{v}$$

Equilibrium *vs.* Steady State

Remember: Electrons flow in opposite direction from conventional current I



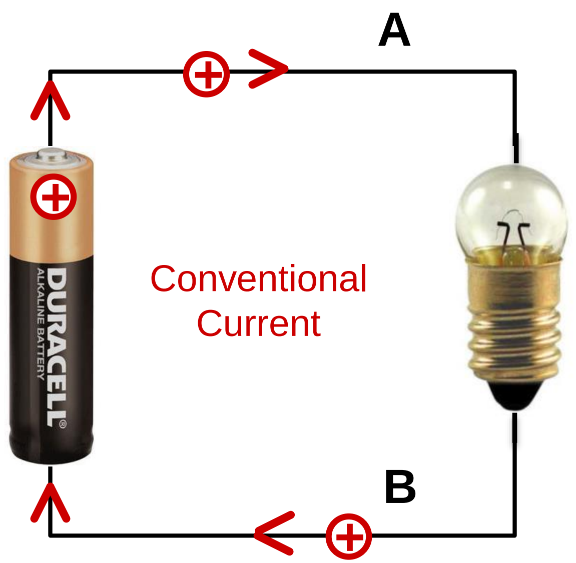
Equilibrium:

- No current flows. Average drift velocity of electrons is zero $\overline{v} = 0$.

Steady State:

- Current flows. Average drift velocity of electrons is $\overline{v} \neq 0$, and it's steady, i.e. it doesn't change over time.
- There is no change in the deposits of excess charge anywhere.

What is the bulb using up?



Can the bulb consume current by destroying electrons?

➔ **No.**

Electrons alone cannot be destroyed → Violation of conservation of charge

Can the bulb consume current as electrons accumulate in the bulb?

➔ **No.**

If there were accumulated electrons, they would repel incoming electrons and stop the current.

Current cannot be used up in the bulb! Current should be the same at A and at B!

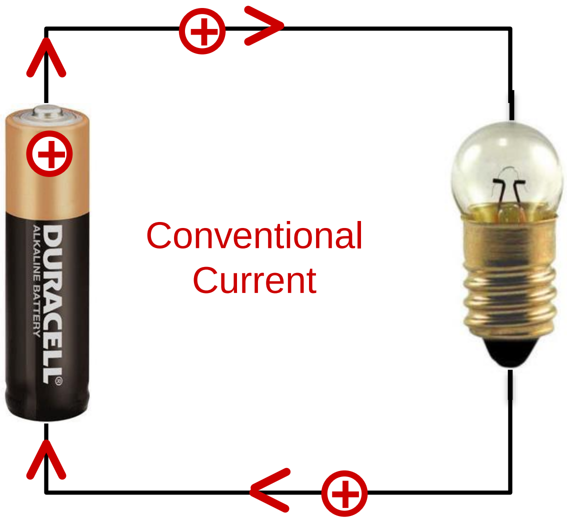
Two conclusions so far,

- **Current cannot be used up in a circuit.**
- **Current is the same everywhere in a series circuit (circuit without parallel branches).**

Still, we didn't answer the question:

What is the bulb using up?

What is the bulb using up?



Energy is being transformed from **Chemical Energy** (stored in the battery) to

Thermal Energy: forcing electrons through the filament produces friction that heats the metal.

Light Energy: photons are emitted by the atoms in the filament.

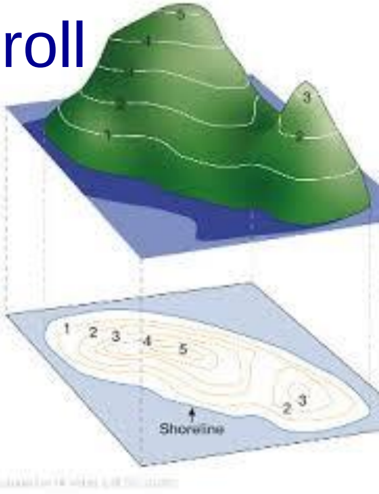
Electric Potential (Voltage) is Like Height

Potential ⟷ Height

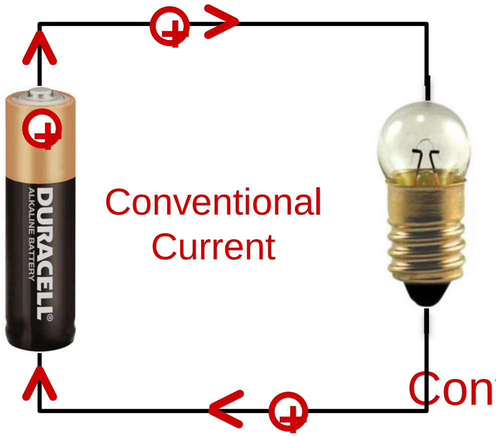
Positive Charge ⟷ Ball

Electric Field ⟷ Slope of hill in the direction ball wants to roll

Lines of Constant Potential ⟷ Contours on a Map



Water Analogy for Current in Circuit

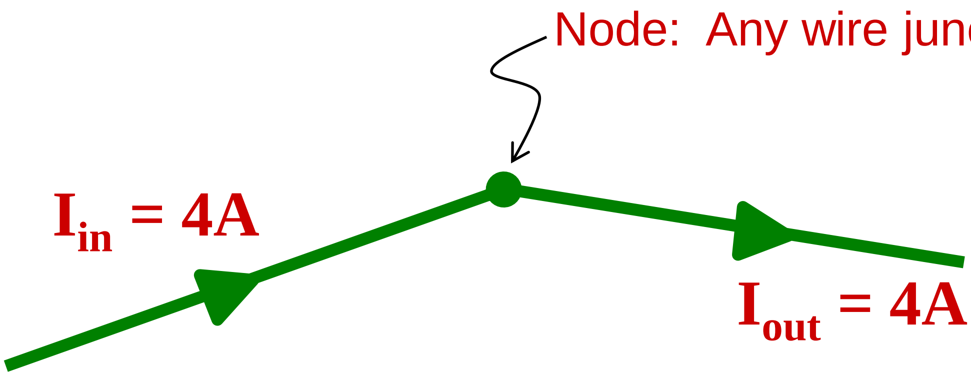


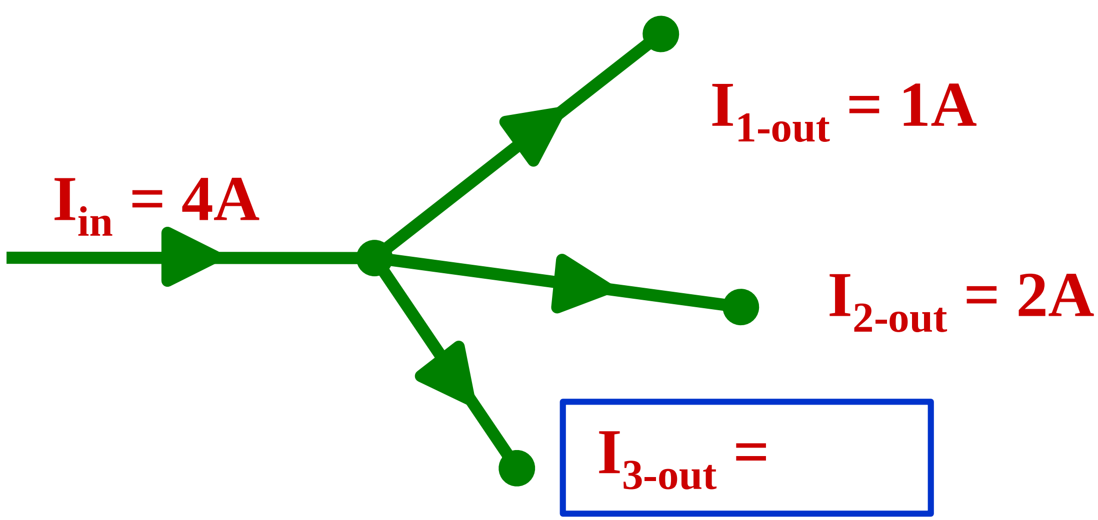
Electrical Circuit	Water Pipes
Positive Charge	Water
Conventional Current	Water Flow (current!)
Voltage	Height
Battery	Pump
Electrical Potential Energy	Gravitational Potential Energy
Current Node Rule	Like water flow in pipe divisions
Voltage Loop Rule	Like height difference along closed pipes
Resistance	~ 1/(pipe diameter)
High Resistance	Skinny pipe
Low Resistance	Fat pipe

Current Node Rule

A.K.A. Kirchhoff's Current Law

Current Node Rule: In the steady state **Current In = Current Out**

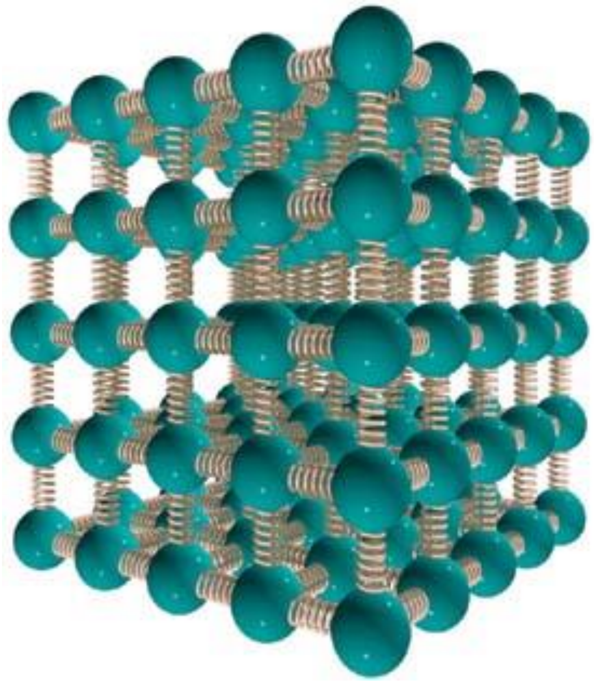




What goes in must come out

Like water through tributaries

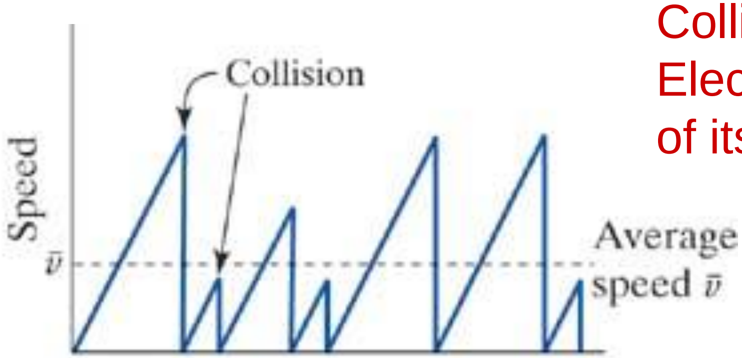
Electric Field in the Circuit



Drude's Model: $\bar{v} = uE$ where $\bar{v} =$ drift speed

$u =$ mobility

Electrons bump into lattice defects/deformations:

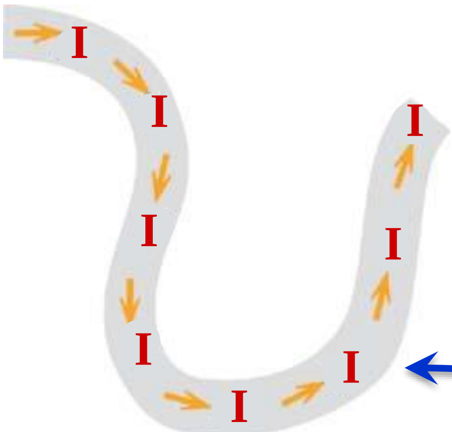


Collision!
Electron loses all
of its kinetic energy.

Need an Electric Field *throughout the wire* to keep the drift speed constant!

Electric Field Inside the Wire

Constant current in the wire ➔ Constant E in the wire.



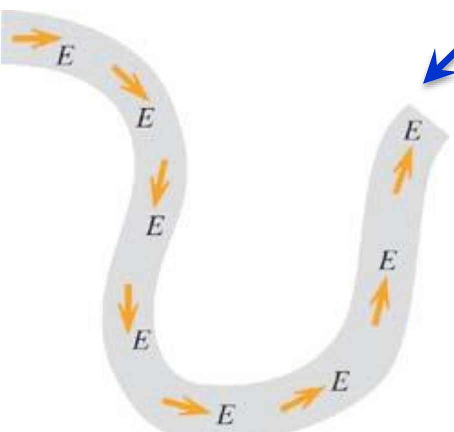
$$I = |q| n A \bar{v}$$

Conventional Current

$$\bar{v} = u|\vec{E}|$$

Drift Velocity controlled by |E|
Mobility (u) set by the material.

If this is true, then this must be true:



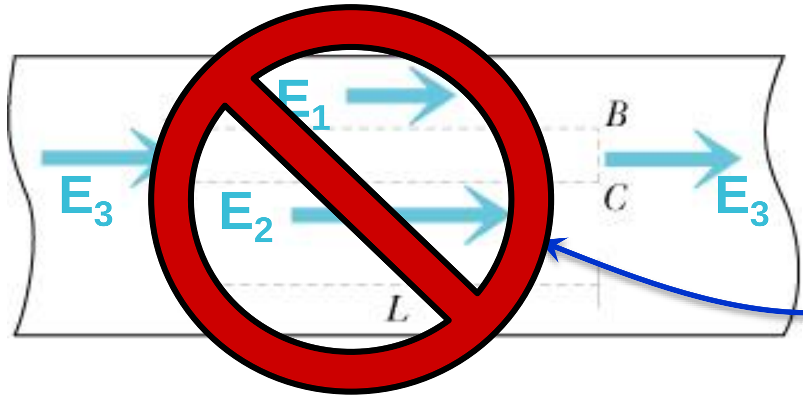
$$I = |q| n A u |\vec{E}|$$

Constant current requires constant |E|

The electric field has to be the same (in magnitude) in every part of the wire where $|q|$, n, A, & u are uniform, also $\vec{E}$ must be parallel to the wire!

Magnitude of Electric Field in a Wire

E must be parallel to the wire   *E* is the same along the wire



Can E be bigger
in the middle of the wire?

If E were bigger in the middle of the wire,
the voltages wouldn't work out.

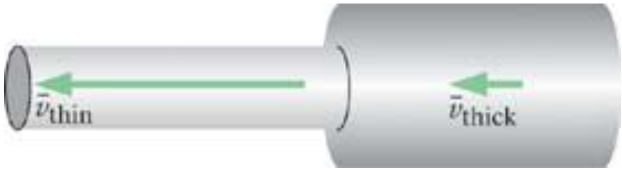
$$\Delta V_{ABCDA} = -\underbrace{\int_A^B \vec{E}_1 \cdot d\vec{l}}_{V_{AB}} - \underbrace{\int_B^C \vec{E}_3 \cdot d\vec{l}}_{0} - \underbrace{\int_C^D \vec{E}_2 \cdot d\vec{l}}_{V_{CD}} - \underbrace{\int_D^A \vec{E}_3 \cdot d\vec{l}}_{0} = 0$$

$$-E_1\, L + E_2\, L = 0 \quad \Rightarrow \quad E_1 = E_2$$

$$\boxed{\text{Magnitude of E is the same across the cross-section of the wire!}}$$

Same Current. Which one is faster?

$$I = |q|nA\bar{v}$$



Think of Water Running Through Pipes

The current is the same anywhere in a series circuit

$$I_{thick} = I_{thin}$$

$$|q|nA_{thick}\bar{v}_{thick} = |q|nA_{thin}\bar{v}_{thin}$$

$$A_{thick}\bar{v}_{thick} = A_{thin}\bar{v}_{thin}$$

$$\bar{v}_{thin} = \frac{A_{thick}}{A_{thin}}\bar{v}_{thick} \Rightarrow \boxed{\bar{v}_{thin} > \bar{v}_{thick}}$$

How about the electric field?

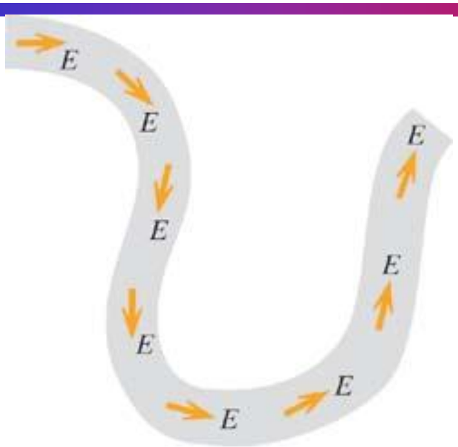
If both sections are made of the same material:

$$A_{thick}\, u\, E_{thick} = A_{thin}\, u\, E_{thin}$$

$$E_{thin} = \frac{A_{thick}}{A_{thin}} E_{thick} \Rightarrow E_{thin} > E_{thick}$$

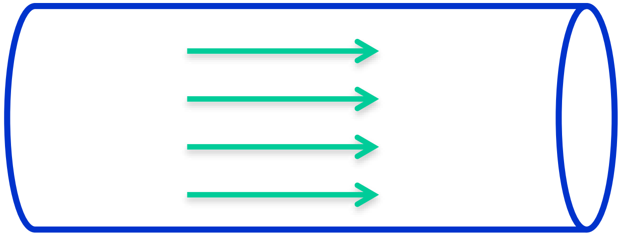
Electric Field Inside the Wire

Constant current in the wire ➔ Constant E in the wire.



$$I = |q|nAu|\vec{E}|$$

Constant current requires constant |E|

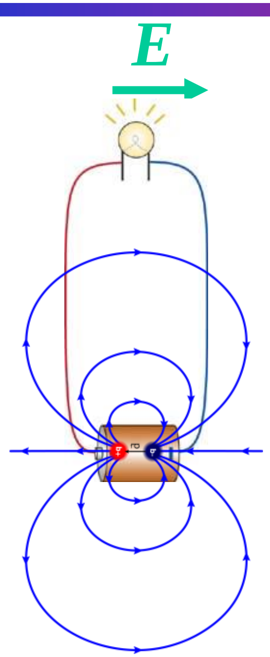


E points in the direction of the wire
|E| is same throughout a wire of uniform cross section and material.

Where are the charges that make the electric field in the wire?

Electric Field in a Wire

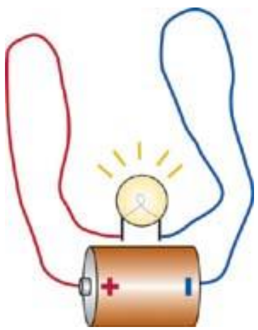
$$I = |q|nAu|\vec{E}|$$



What charges make the electric field in the wires?

Is it just due to excess charges on the battery?

Try This:



If battery is something like an electric dipole:
1. E has to increase when we move light bulb close to it →much brighter bulb.
2. Turning the wire 90º→bulb brightness should change

Nothing of this happens!

E in the wire can't just be due to excess charges on battery!

Field due to the Battery→ Not enough!

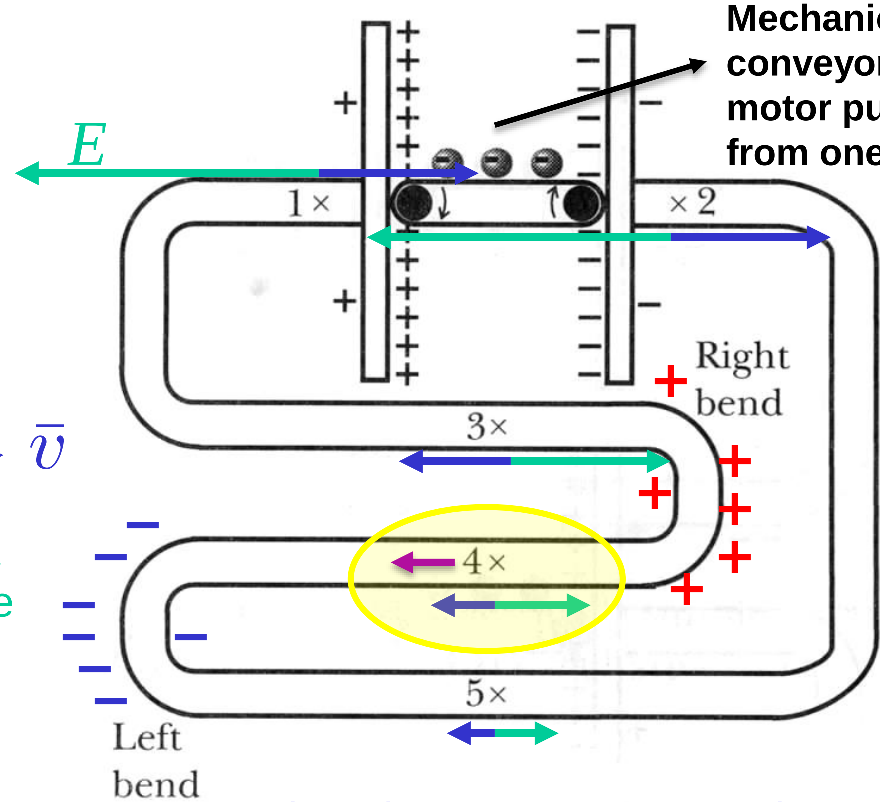
Assume:

1) (CORRECT) Battery has some way to maintain constant charge at its terminals.

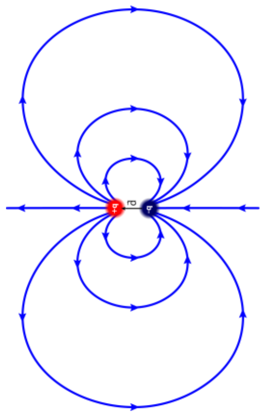
2) (WRONG!) E is due only to dipole field of Battery.

E due to dipole

E due to charge on the bends



Mechanical battery: conveyor belt driven by motor pushes electrons from one plate to the other.

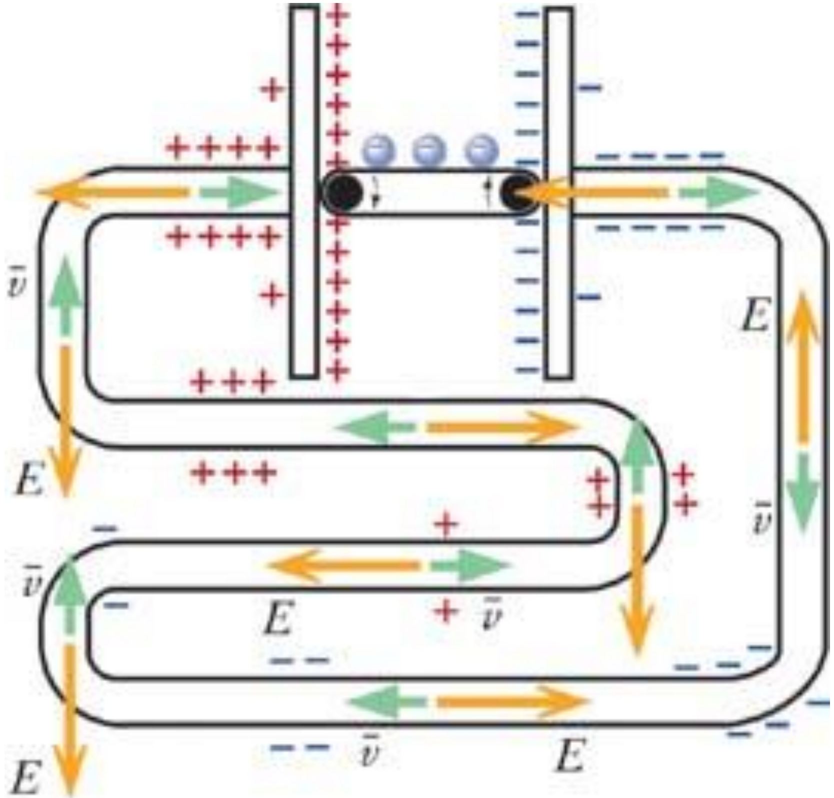


Transient state (before steady state): The pileup of charge at the bends will continue until the net electric field at 4 points to the left!

Other charges must appear in various places on the surface of the wire so that the electric fields at 3, 4, & 5 have the same magnitude and point in the direction of the conventional current.

FEEDBACK! Any deviation away from the steady state will produce a change that tends to restore it!

Field due to the Battery



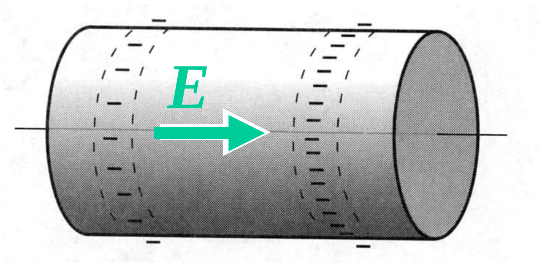
In the steady state, surface charge arranges itself in such a way as to produce a pattern of electric field that follows the direction of the wire and has such a magnitude that current is the same along the wire!

Where are the charges that cause E?

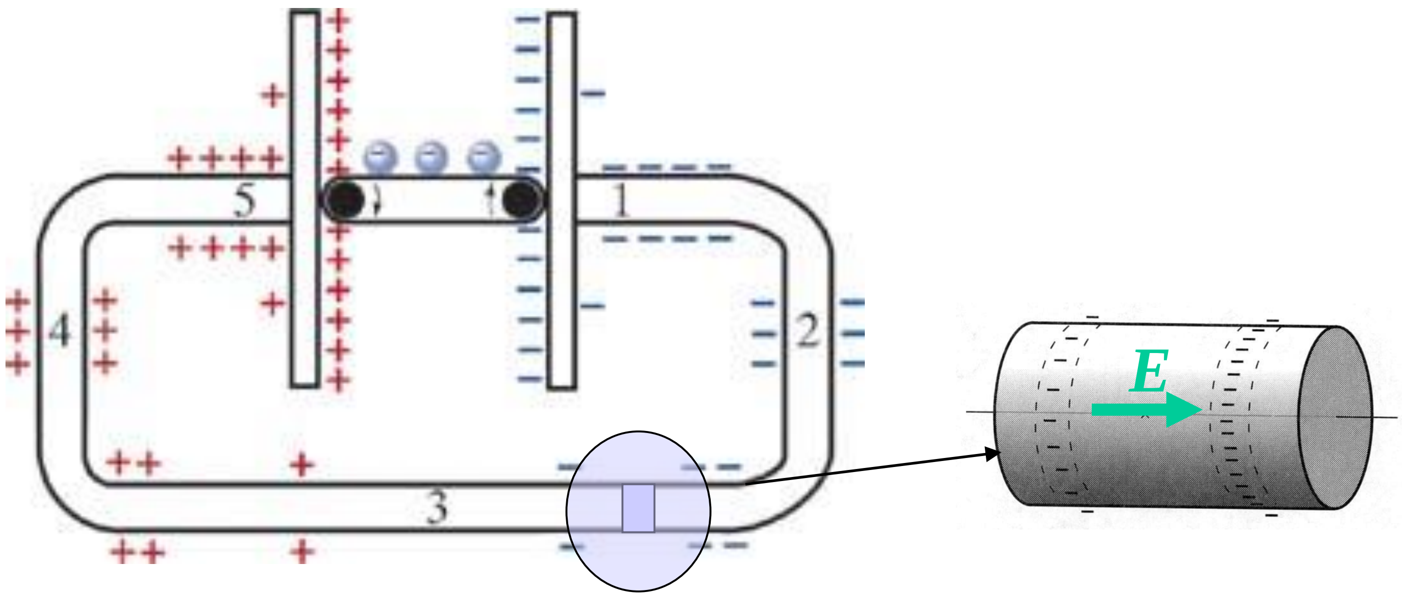
Excess charge goes to the surface of a conductor

Simplest model for long straight sections of wire:

- Surface charge arranged in a series of rings of charge.
- Constant charge gradient → uniform electric field



Where are the charges which cause E?

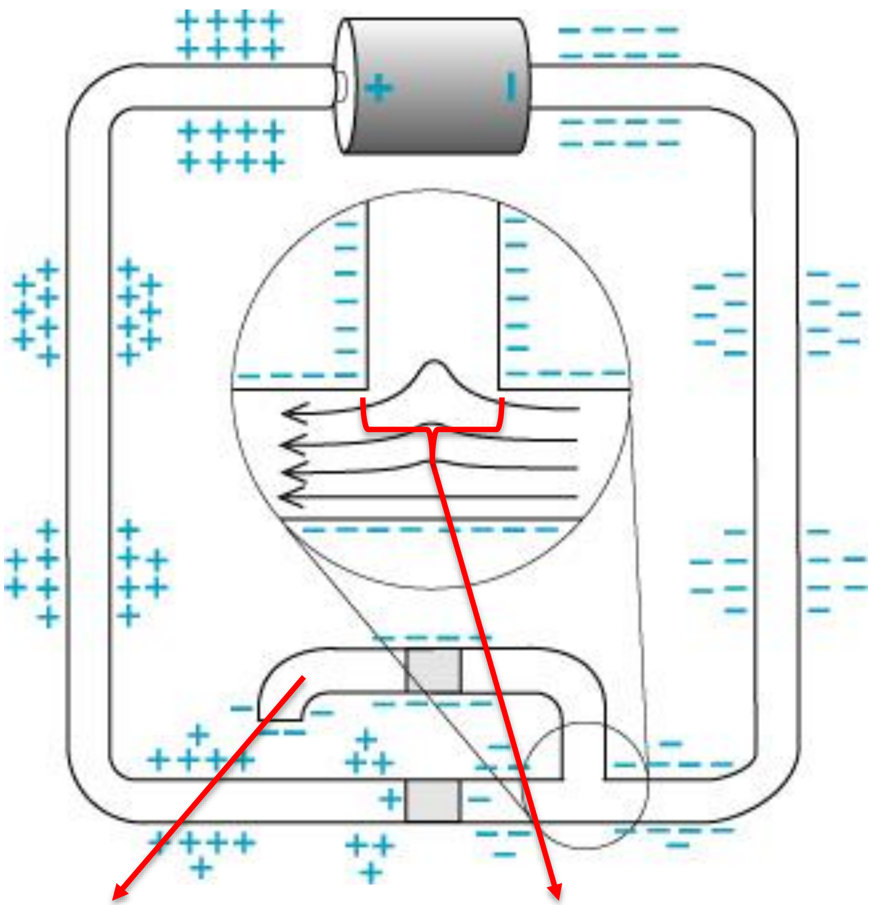


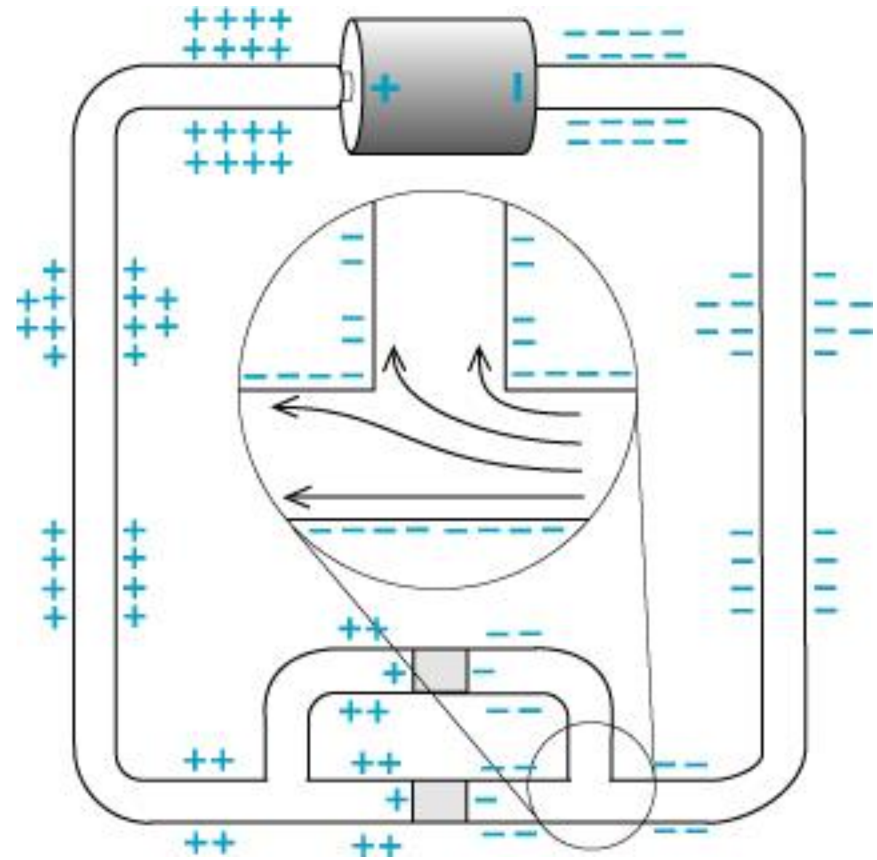
- On long straight sections of wire far from other circuit elements → nearly constant gradient of surface charge.

- The surface charge gradient is greater in regions of the circuit where the electric field is larger.

- The distribution of surface charge is complex in sharp bends or where two different elements are connected.

How Do the Currents Know How to Divide?





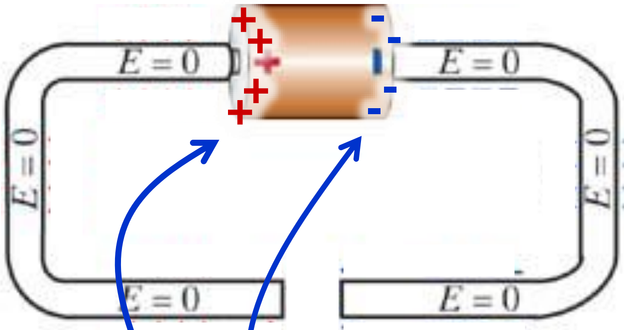
Dead end: built up of negative charge → no more electrons can enter

Interruption of negative surface charge → like wider wire → defletion of electron stream lines

Complete parallel connection → new arrangement of surface charge → mobility in each branch determines the fraction of current that goes down that branch.

Connecting a Circuit

What happens just before and just after a circuit is connected?



Before the circuit is connected:

- No current flows $I = |q|nAu|\vec{E}| = 0$
- System is in ***equilibrium:***

$$\vec{E} = 0$$

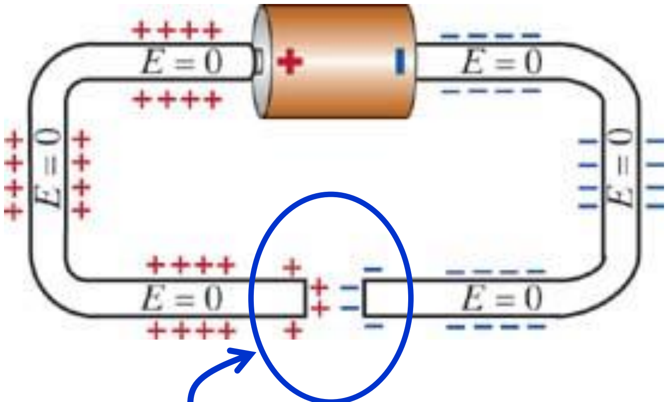
$$\bar{v} = u|\vec{E}| = 0$$

How is |E| = 0 maintained when there are charges here?

There must be surface charges distributed on the wire to keep E=0 everywhere inside the wires.

Connecting a Circuit

What happens just before and just after a circuit is connected?



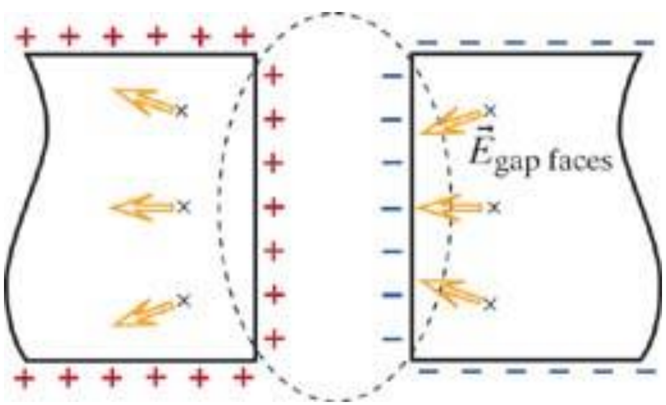
Think about the gap...
There is a large concentration of surface charge near the gap.

Before the circuit is connected:

- No current flows $I = |q|nAu|\vec{E}| = 0$
- System is in ***equilibrium:***

$$\vec{E} = 0$$

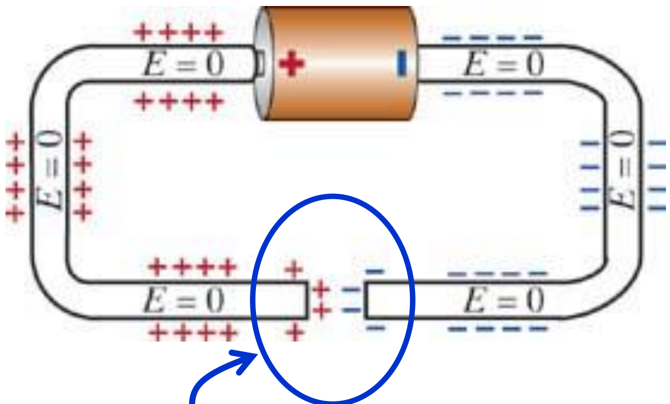
$$\bar{v} = u|\vec{E}| = 0$$



Think about **E** due only to gap faces

Connecting a Circuit

What happens just before and just after a circuit is connected?



Think about the gap...

Before the circuit is connected:

- No current flows $\quad I = |q|nAu|\vec{E}| = 0$
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$$\vec{E} = 0$$

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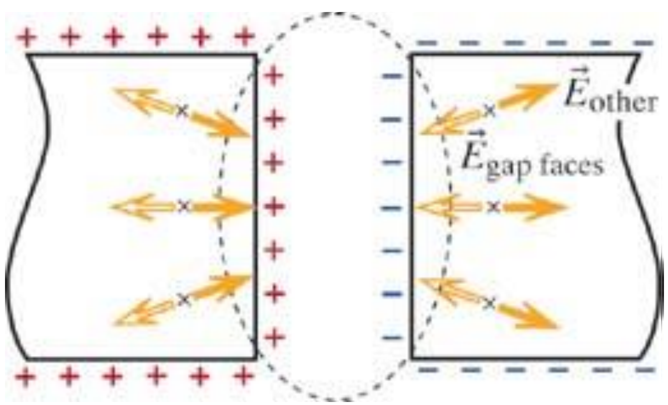
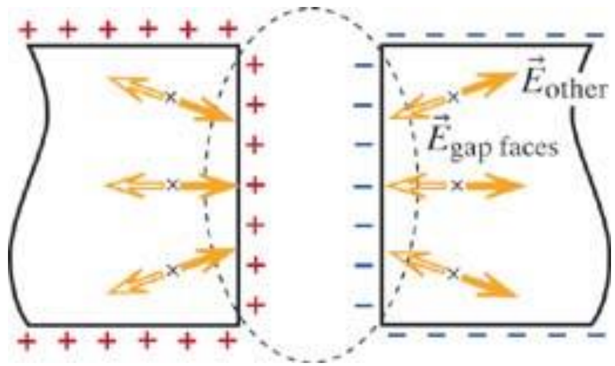


E due to everything else cancels $\mathbf{E}_{gap}$ since $E_{net} = 0$

Connecting a Circuit

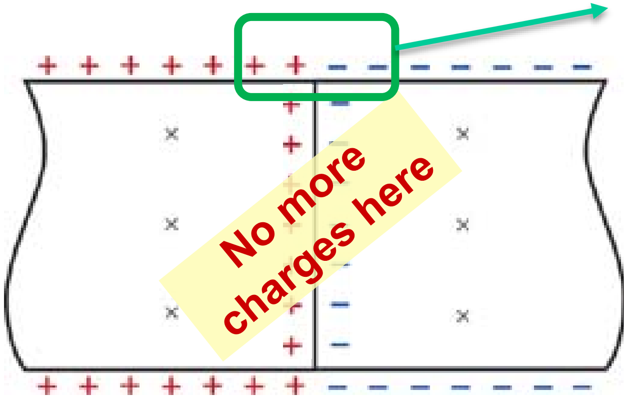
What happens just before and just after a circuit is connected?

Before the circuit is connected:



E due to everything else cancels $\mathbf{E}_{gap}$

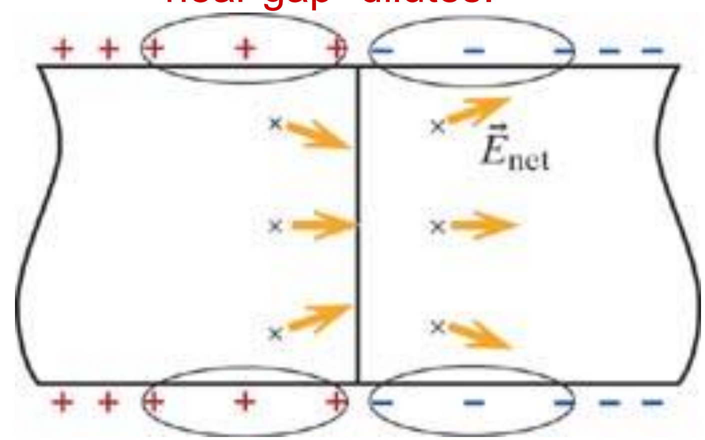
Now close the gap → transient state



Unstable discontinuity in surface charge distribution

Electrons will start moving to the left

Gradient of surface charge near gap degreases, surface charge near gap "dilutes."

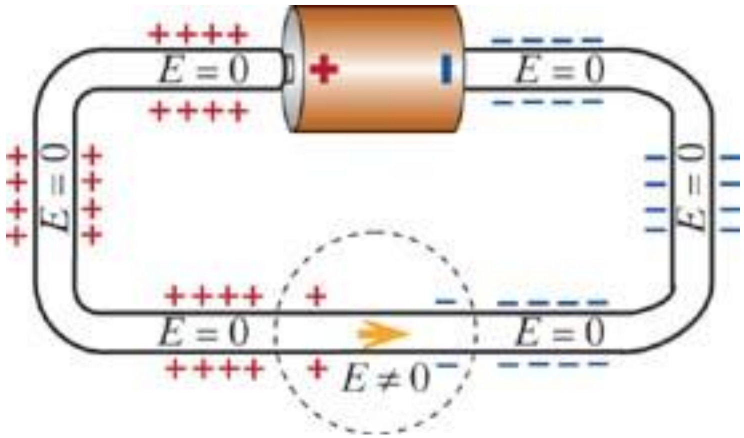


The gap face charge → 0, and so does $\mathbf{E}_{gap}$

Connecting a Circuit

What happens just before and just after a circuit is connected?

Just after the circuit is connected: Transient State



There is a **disturbance** in the previous (equilibrium) E-field.

Now the region next to the disturbance updates its E-field, and the next region... Until the steady state is achieved!
→ E = const. inside the wire

How fast does this disturbance propagate?

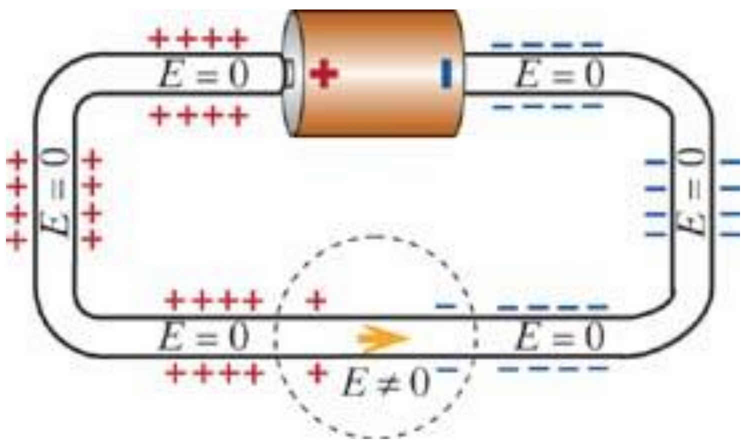
At the drift speed of the electrons? $\bar{v} \approx 5 \times 10^{-5} m/s$

At the speed of light? $c \approx 3 \times 10^{8} m/s$

Connecting a Circuit

What happens just before and just after a circuit is connected?

Just after the circuit is connected:



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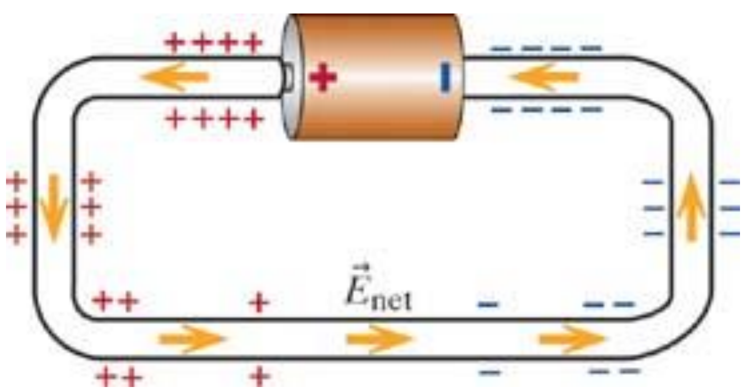
Now the region next to the disturbance updates its E-field, and the next region...



The disturbance travels at the speed of light, and within a few **nanoseconds**, **steady state** is established.

Today

- Equilibrium *vs*. Steady State
- What is "used up" in a circuit?
  - Nothing -- Energy is converted
- Kirchhoff's Current Node Law
- **E**-field inside a wire is due to surface charges