Last Time

- Magnetic Field of a Straight Wire
- Magnetic Field of a Current Loop
- Magnetic Dipole Moment
- (Bar Magnet)
- (Electron Spin)

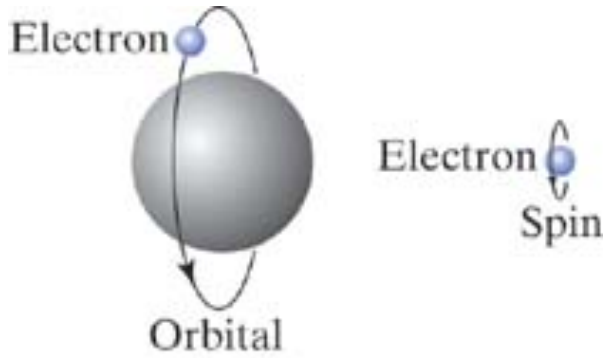
Today

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

Quantum Magnetism

Magnetic Moment = Orbital Motion + "Spin"

SPIN:



Electron acts like spinning charge

- contributes to μ

Electron spin contribution to μ is of the same order as one due to orbital momentum

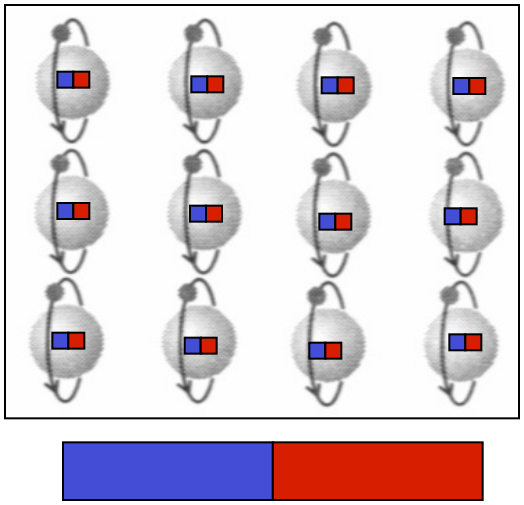
Neutrons and proton in nucleus also have spin but their μ's are much smaller than for electron

same angular momentum: $\mu \approx \frac{1}{2}\frac{e}{m}\hbar$

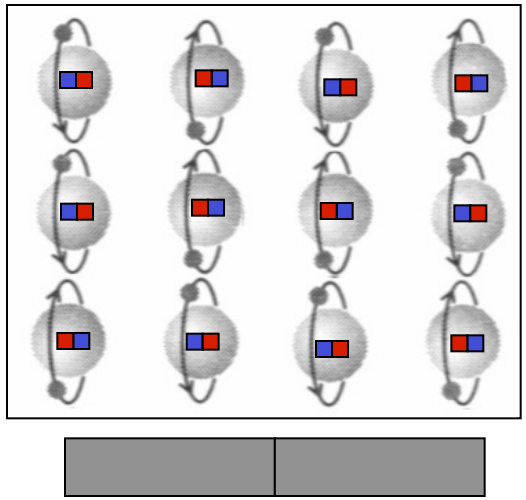
NMR, MRI – use nuclear μ

Refrigerator Magnets

Alignment of atomic dipole moments:



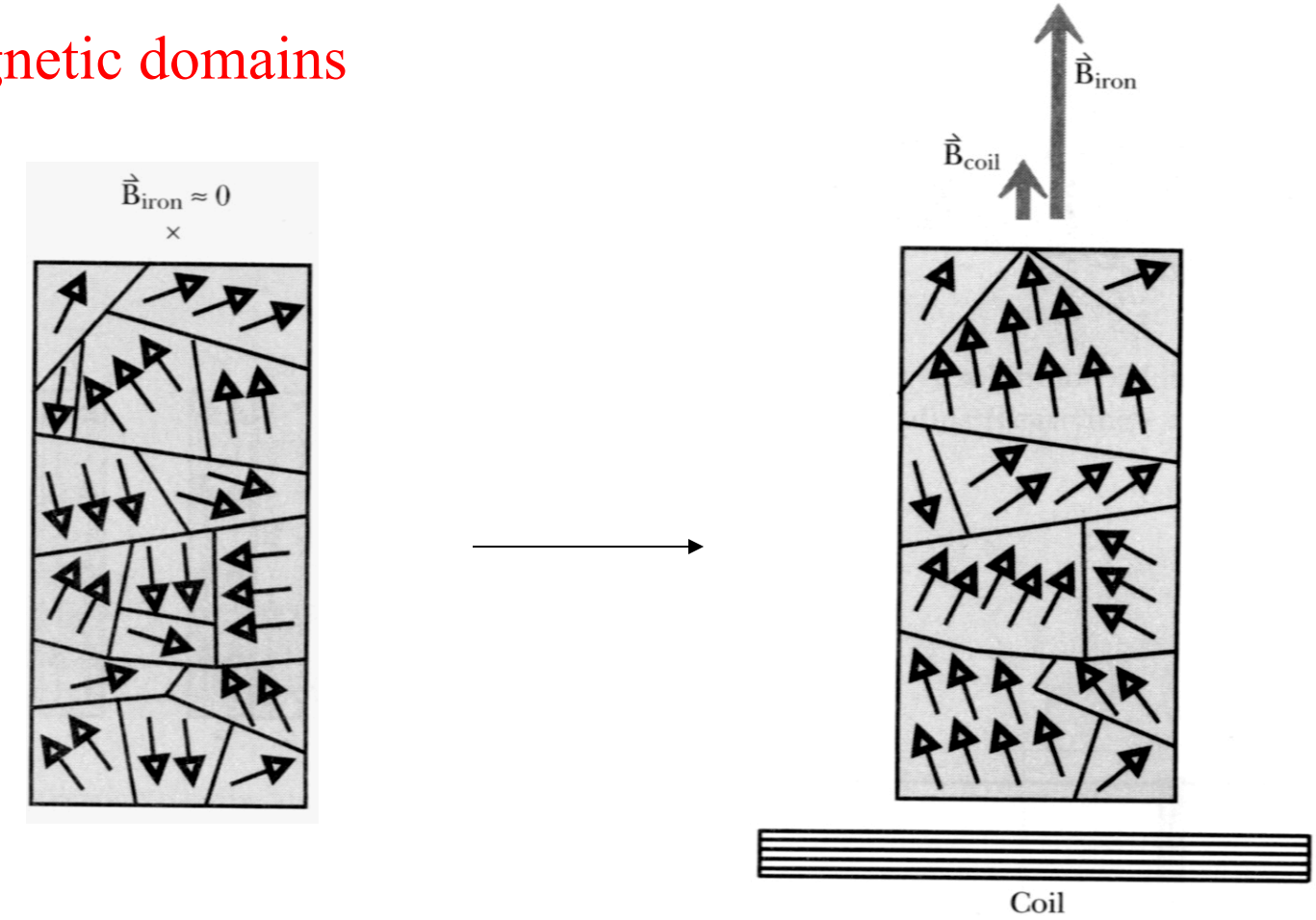
ferromagnetic materials:
iron, cobalt, nickel



most materials

Reality Physics - Domains

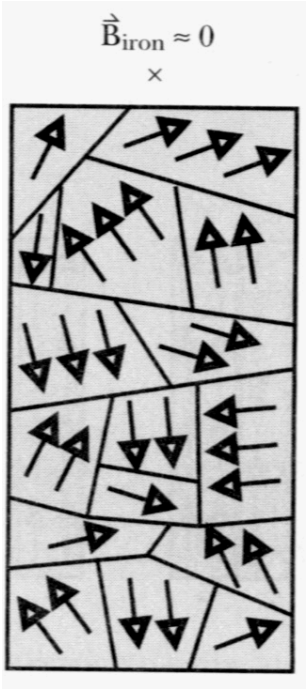
Magnetic domains

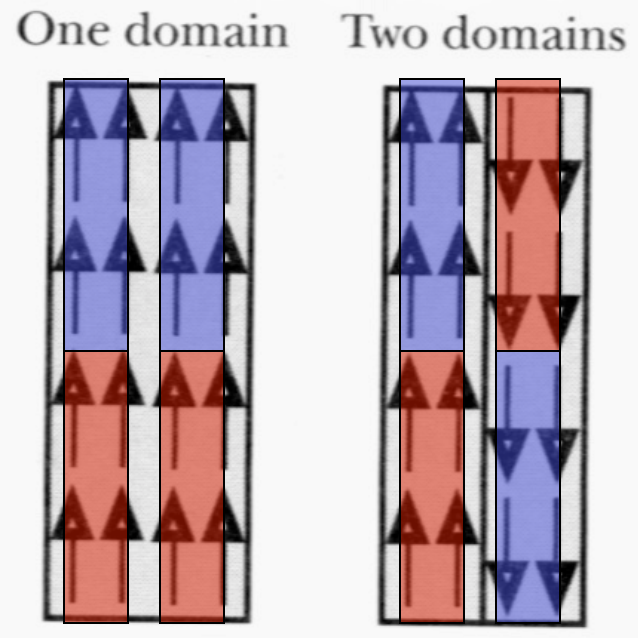


Hitting or heating can also demagnetize

Why are there Multiple Domains?

Magnetic domains





Key Ideas in Chapter 19: Electric Circuits

- **Surface charges 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.

Overview of Circuits

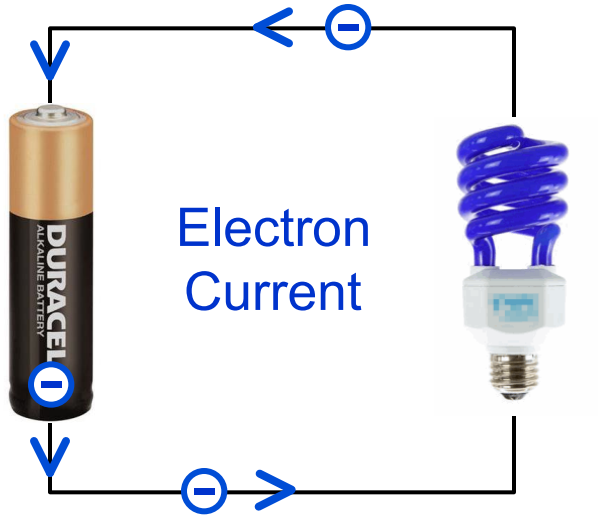
Microscopic Questions:

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

Equilibrium *vs*. Steady State

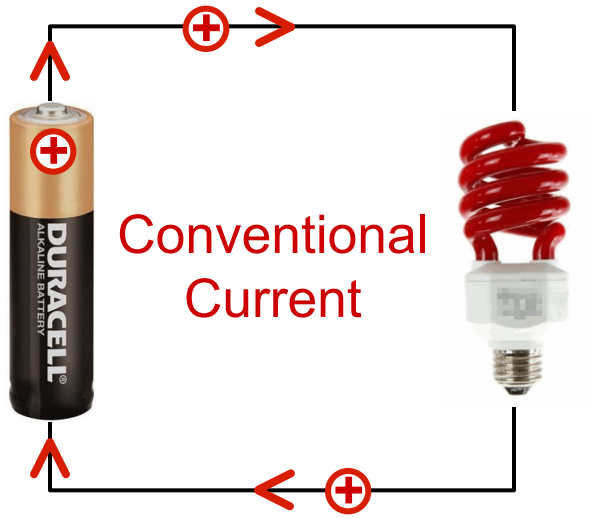
- Are charges used up in a circuit?
- Exactly how does a current-carrying wire create and maintain nonzero E inside?
- What does the battery do?

Conventional Current and Electron Current



Electron Current:

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

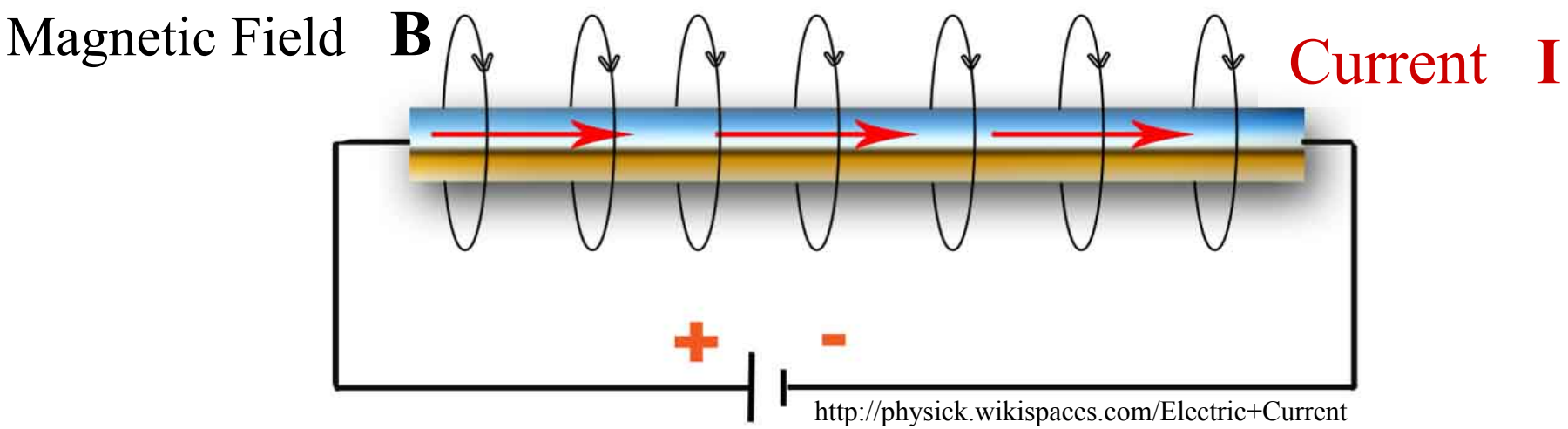


Conventional Current:

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

Equilibrium *vs.* Steady State

Remember: Electrons flow in opposite direction from conventional current I



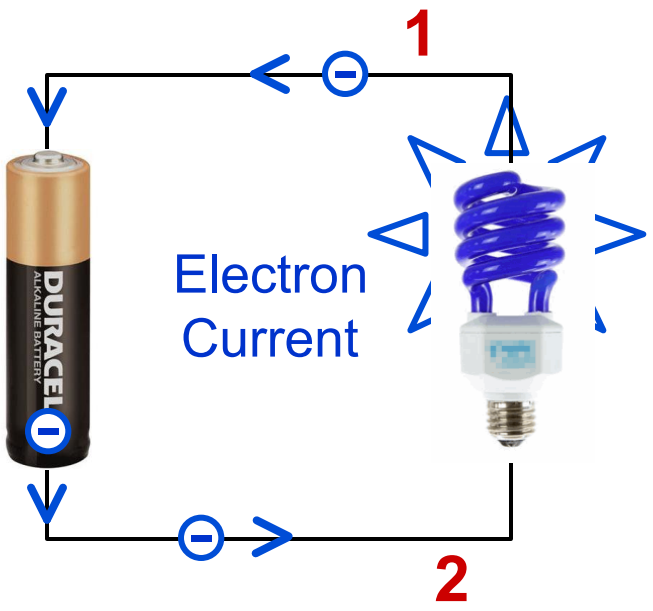
Equilibrium:

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

Current Flow is not Equilibrium, but it is Steady State.

- Current flows. Average drift velocity of electrons is ***constant*** $\bar{v} = \text{const.}$

Clicker Poll (Participation grade only)



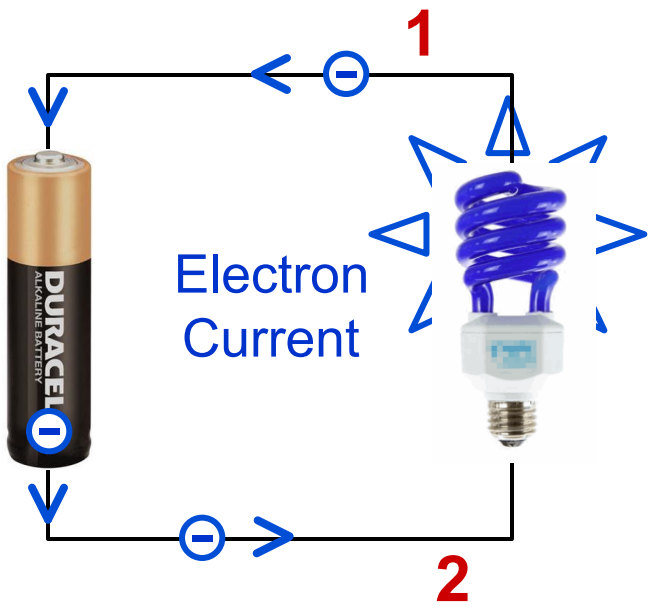
How would you expect the amount of current at location 1 to compare to the electron current at location 2?

A) There is no current at 2, since the bulb used it up.

B) There is less current at 2 than at 1, since some of it gets converted to light and heat given off by the bulb.

C) The current at 2 is the same as the current at 1.

What IS the bulb using up?



Can the bulb consume current by destroying electrons?

➔ **No.**

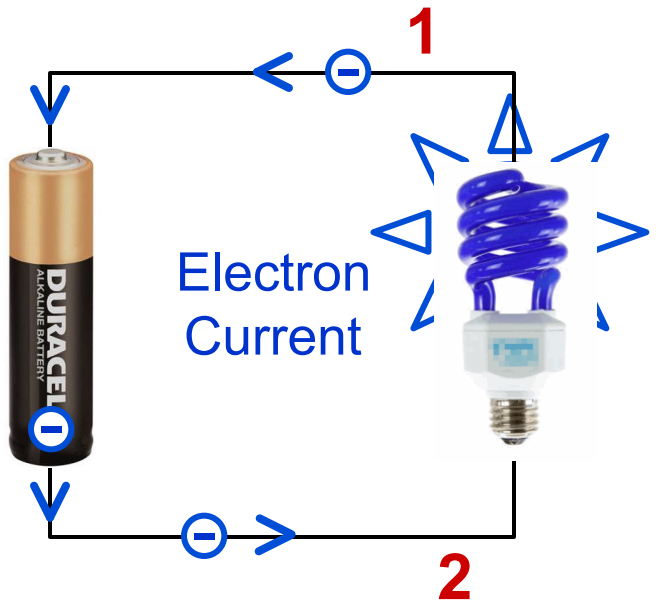
Electrons cannot be destroyed.

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

➔ **No.**

Otherwise electric field would change

What IS the bulb using up?



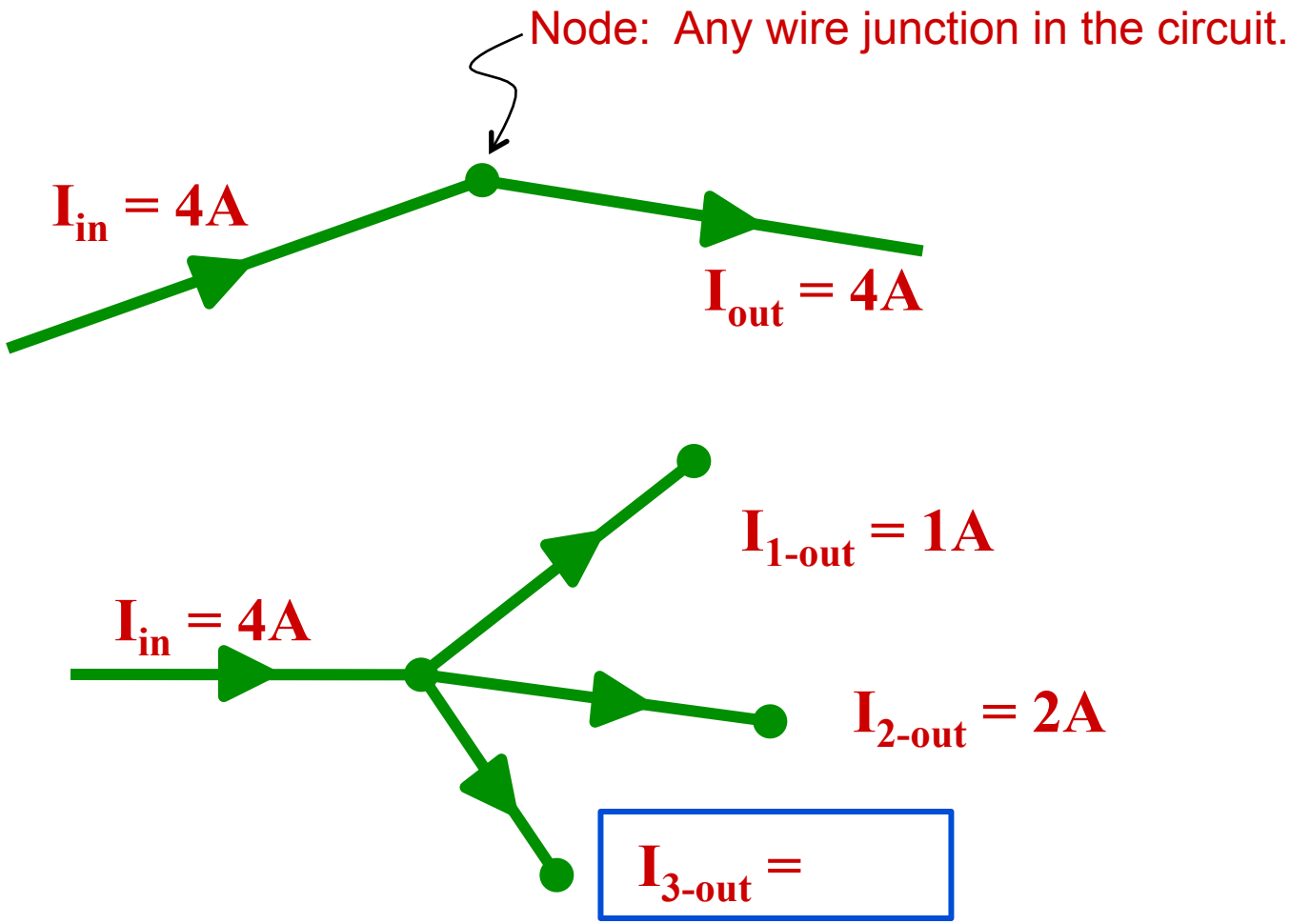
Chemical Energy of battery converts to:

Light Energy
Heat Energy

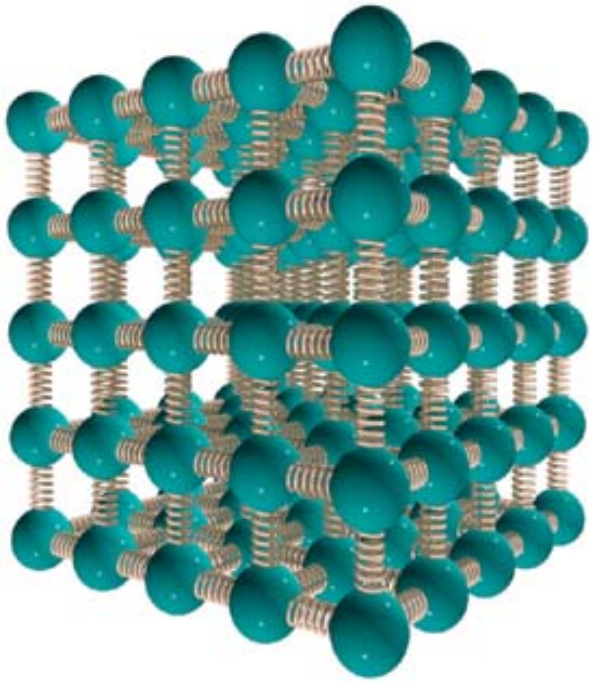
Current Node Rule

A.K.A. Kirchhoff's Current Law

Current Node Rule: **Current In = Current Out**

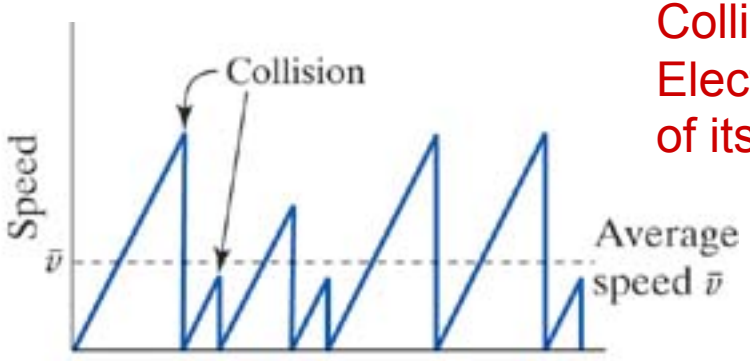


Electric Field in the Circuit



Electrons can surf through a lattice by finding the right wavelength.

But they do bump into lattice defects/deformations:

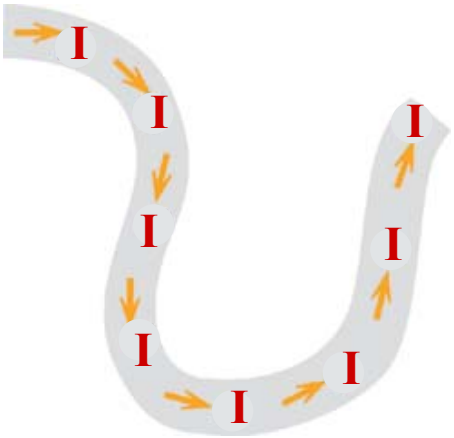


Collision!
Electron loses all of its kinetic energy.

Need an Electric Field *throughout the wire* to re-accelerate the electrons.

Electric Field Inside the Wire

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

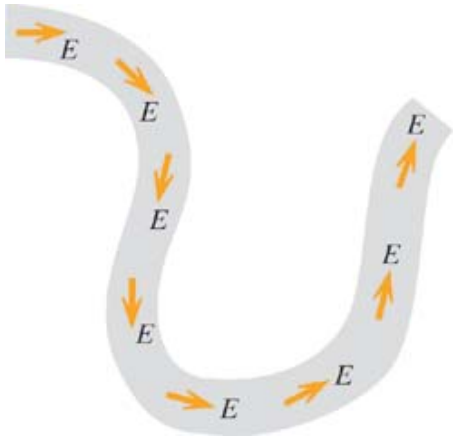


$$I = |q| n A \bar{v}$$

Conventional Current

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

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



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

Constant current requires constant |E|

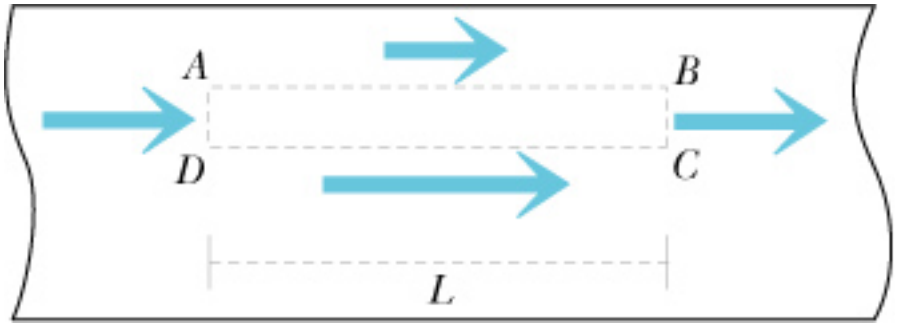
Direction of Electric Field in a Wire

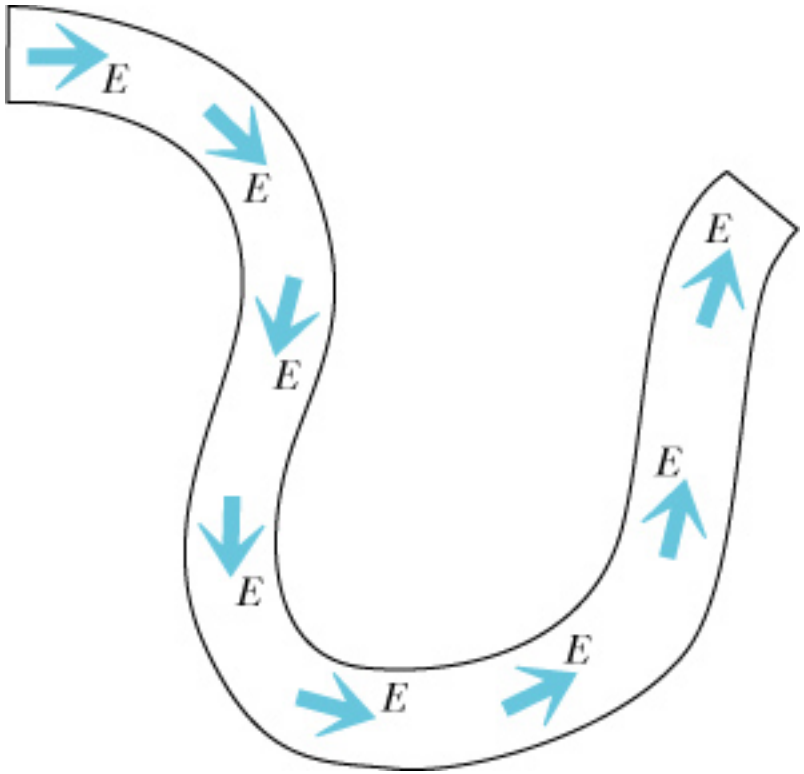
E must be parallel to the wire

E is the same along the wire

Does current fill the wire?

Is *E* uniform across the wire?



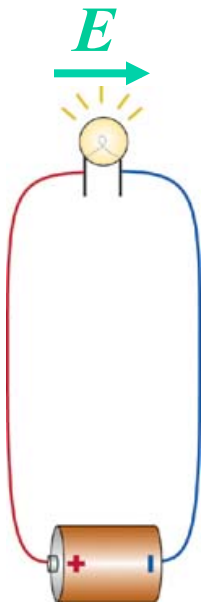


$$\Delta V_{ABCDA} = -\underbrace{\int_{A}^{B} \vec{E}_1 \cdot d\vec{l}}_{V_{AB}} - \underbrace{\int_{B}^{C} \vec{E}_3 \cdot d\vec{l}}_{0} - \underbrace{\int_{C}^{D} \vec{E}_2 \cdot d\vec{l}}_{V_{CD}} - \underbrace{\int_{D}^{A} \vec{E}_3 \cdot d\vec{l}}_{0} = 0$$

$$\vec{E}_1 = \vec{E}_2$$

Electric Field in a Wire

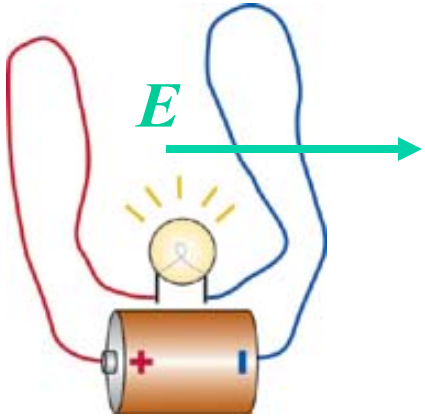
What charges make the electric field in the wires?



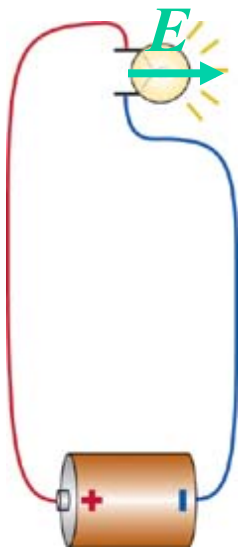
Bulb filament and wires are metals –
there cannot be excess charges in the interior

Are excess charges on the battery?
ASSUME: E due to dipole field of battery.

This cannot be the source of the E which drives current.



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

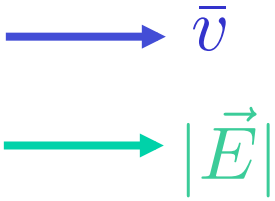


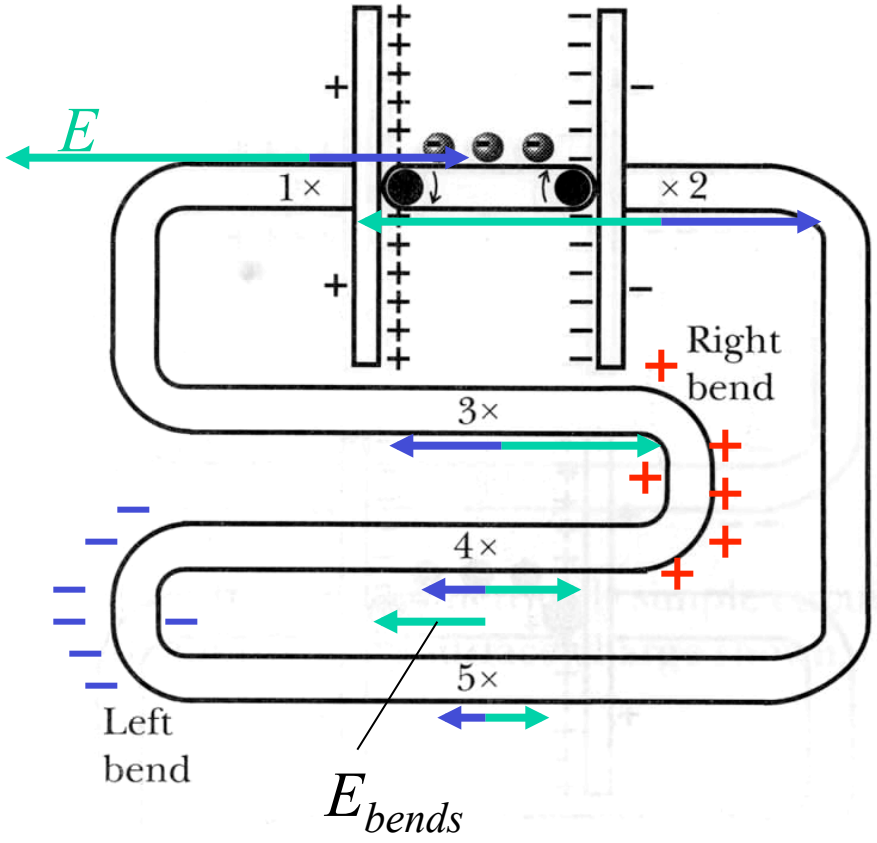
Field due to the Battery

Assume:

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

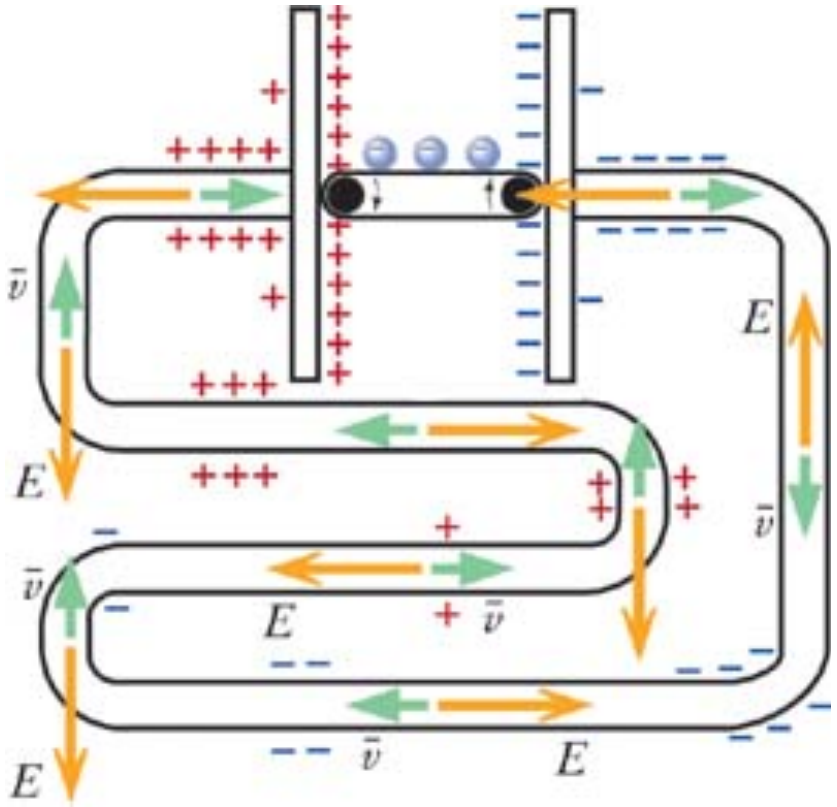
2) (WRONG!) E is due only to dipole field of Battery.





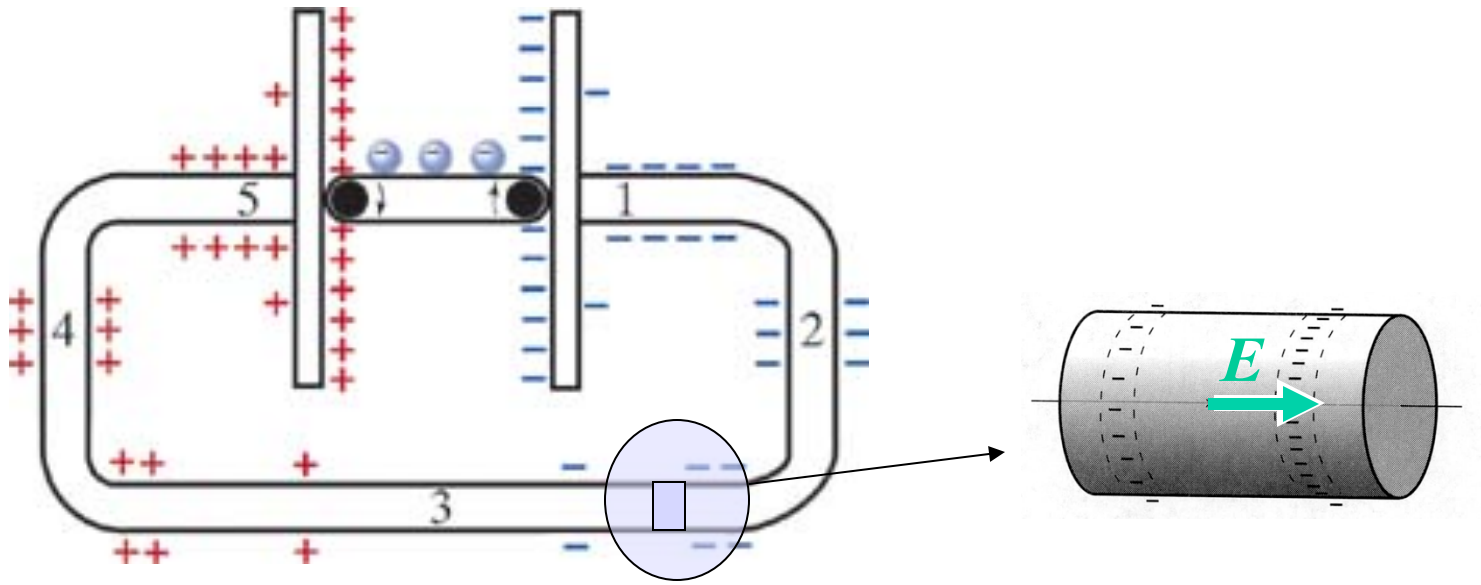
In the steady state there must be some other charges somewhere that contribute to the net electric field in such a way that the electric field points upstream everywhere.

Field due to the Battery



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.

Field due to Battery



Smooth transition from + surface charge to – to provide constant *E*.

The amount of surface charge is proportional to the voltage.

Today

- Electron Spin
- Bar Magnet
- 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