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.

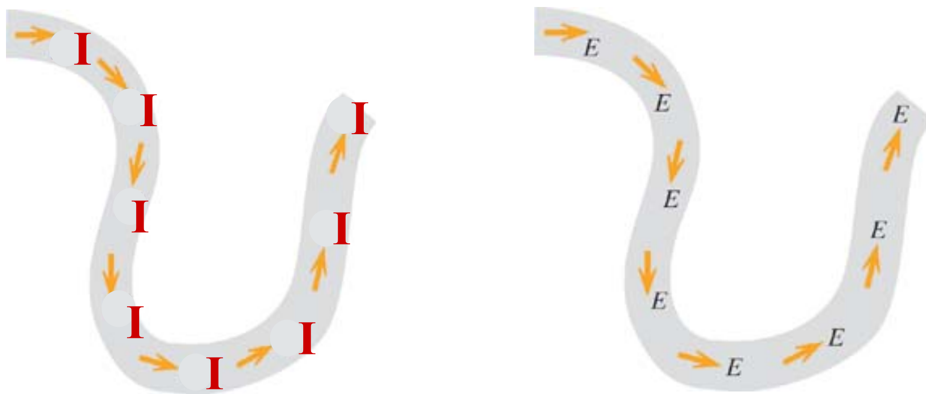
- **How to analyze circuits:**
  - Current-node rule: Current into a node equals current out of the node.
  - Voltage-loop rule: The total potential difference around a loop is zero.

Last Time

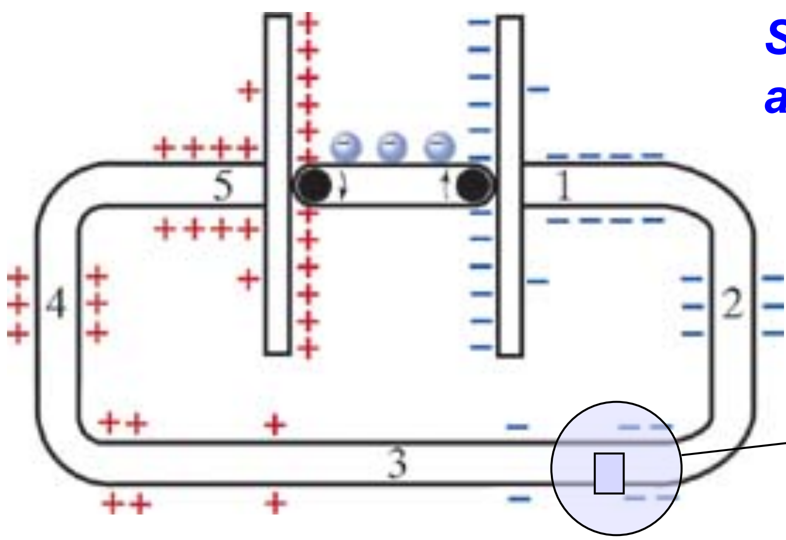
- Electron Spin
- Bar Magnet
- Equilibrium *vs*. Steady State in a Circuit
- What is "used up" in a circuit?
- Kirchhoff's Current Node Law
- **E**-field inside a wire

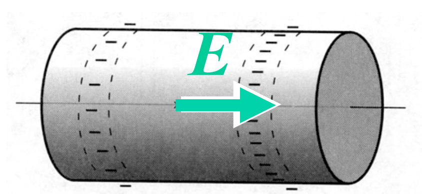
Microscopic View of E in the wire:

Constant current in the wire → Constant E in the wire.



Surface charges on wire automatically adjust so as to maintain constant E in the wire.



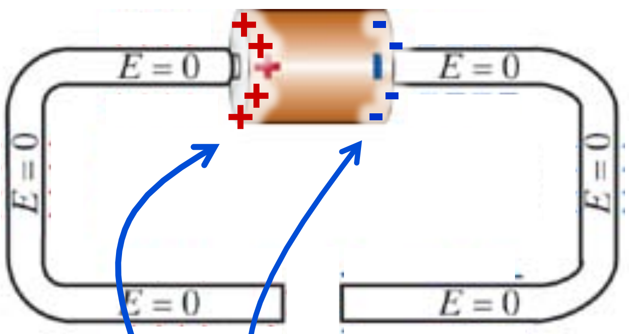


Today

- Transient response when connecting a circuit
- How long until steady state is reached?
- Introduction to Resistors
- Energy conservation in a circuit
- Kirchhoff's Voltage Loop Law
- Batteries

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 on the wire
to prevent current from flowing before we connect the circuit.

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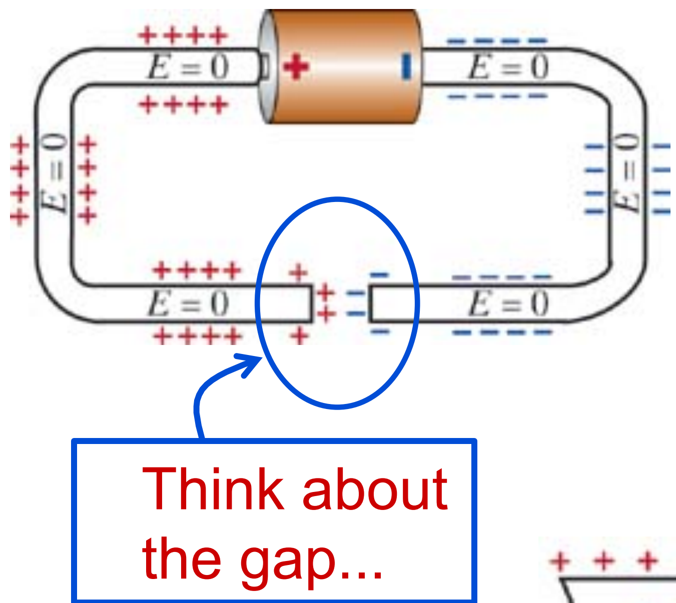

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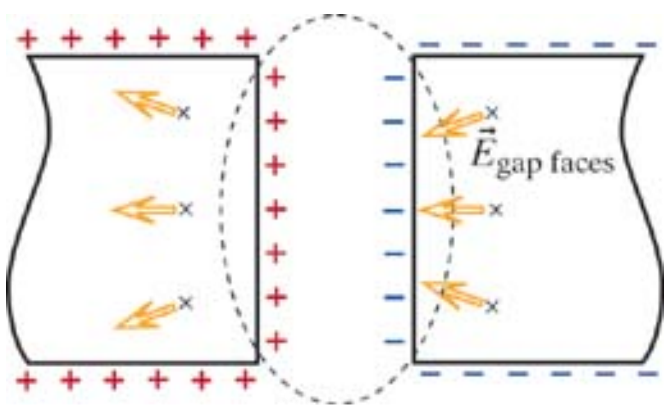

E due only to gap faces

Connecting a Circuit

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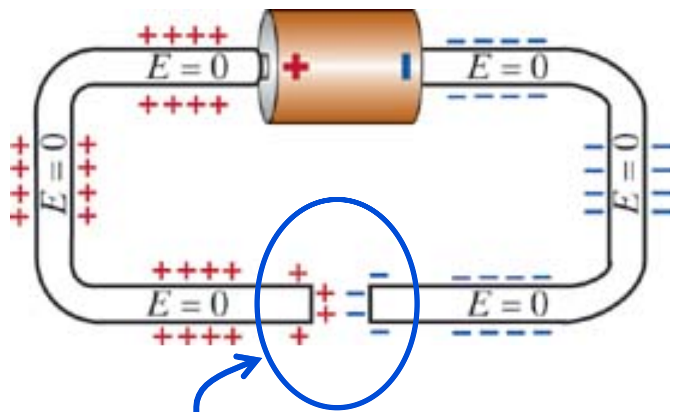

Think about the gap...

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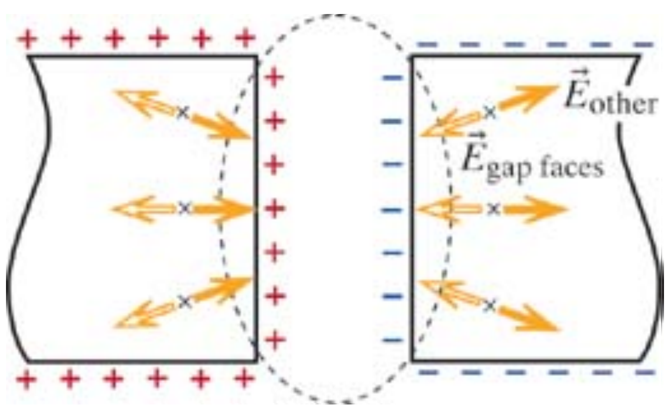

E due to everything else cancels $\mathbf{E}_{gap}$

Connecting a Circuit

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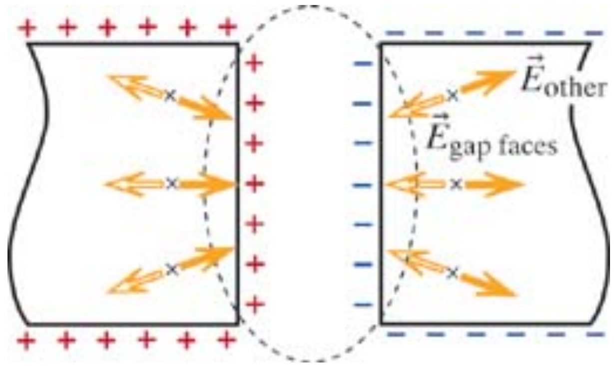
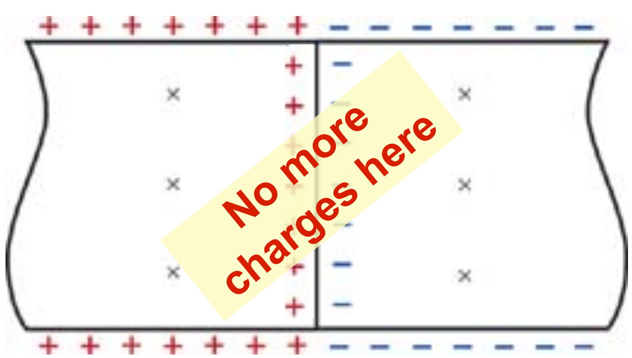
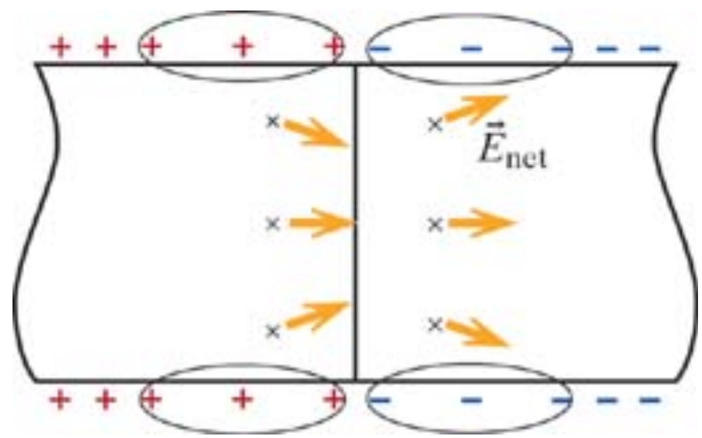


E due to everything else cancels $\mathbf{E}_{gap}$

Now close the gap ...



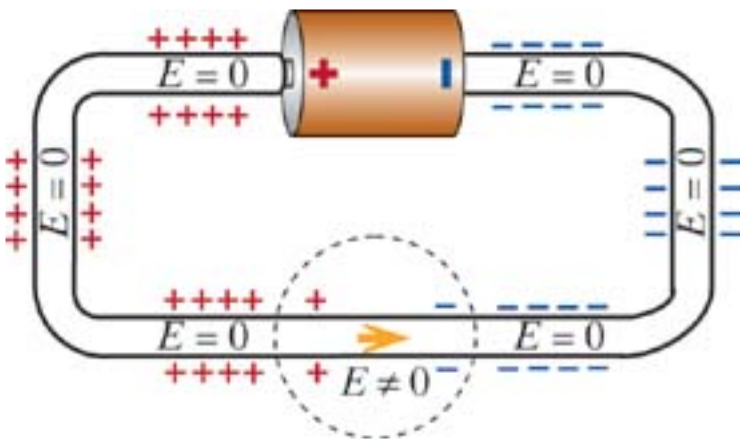


The gap face charge → 0, and so does $\mathbf{E}_{gap}$

Connecting a Circuit

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

Just after the circuit is connected:



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...

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? $c \approx 3 \times 10^{8} m/s$

iClicker – Reality Physics!

$\bar{v} \approx 5 \times 10^{-5} m/s$ Drift speed of electrons

$c \approx 3 \times 10^{8} m/s$ Speed of light

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Reality Physics!

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Flip Light Switch On.

How long until information about the change in E-field reaches the light bulb?

L = 5 m

≈ 1 day for electrons to travel from light switch to bulb.

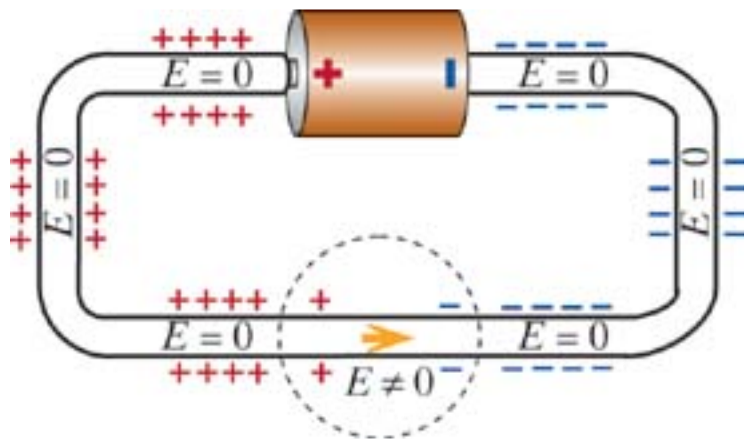
≈ 16 nanoseconds for the change in E-field to travel from light switch to bulb.

Because there are sooooo many electrons in the wire, they don't have to move far to create a large current.

Connecting a Circuit

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

Just after the circuit is connected:



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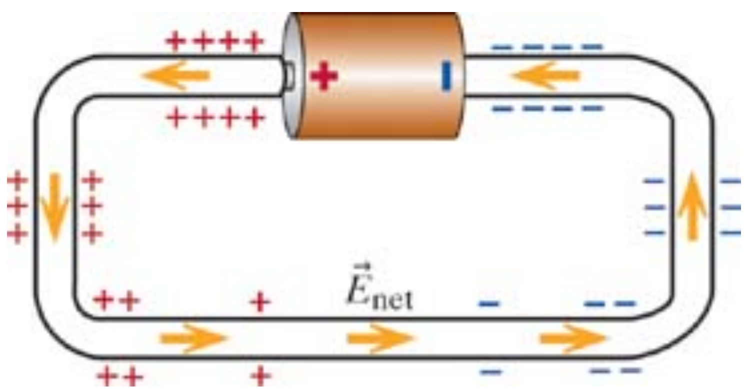
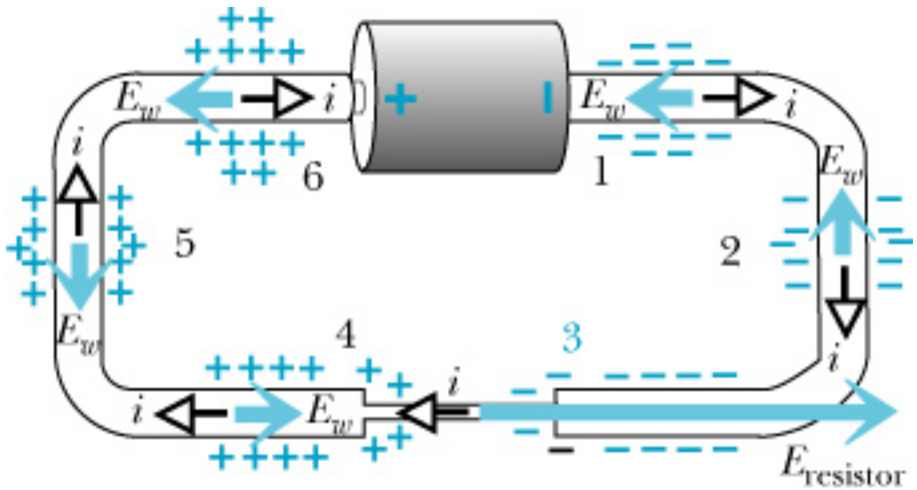


The disturbance travels at the speed of light, and within a few **nanoseconds**, **steady state** is established.

Surface Charge and Resistors



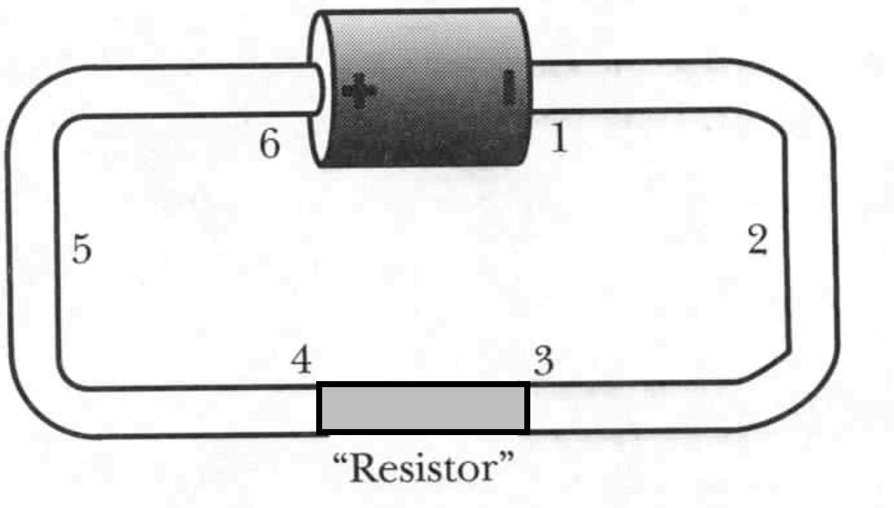
After steady state is reached:

$$i_{thin} = i_{thick} \longrightarrow \boxed{E_{thin} = \frac{A_{thick}}{A_{thin}} E_{thick}}$$

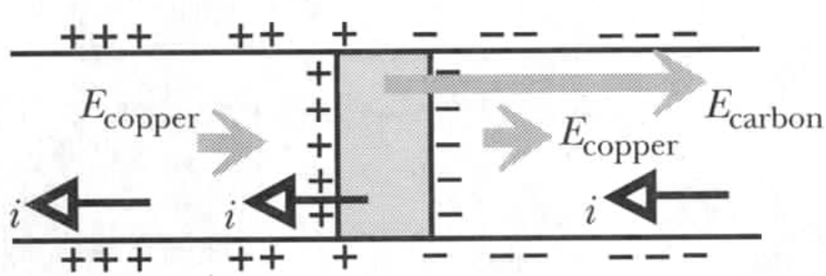
$$i_{thin} = nA_{thin}uE_{thin}$$

$$i_{thick} = nA_{thick}uE_{thick}$$

A Wide Resistor



low mobility



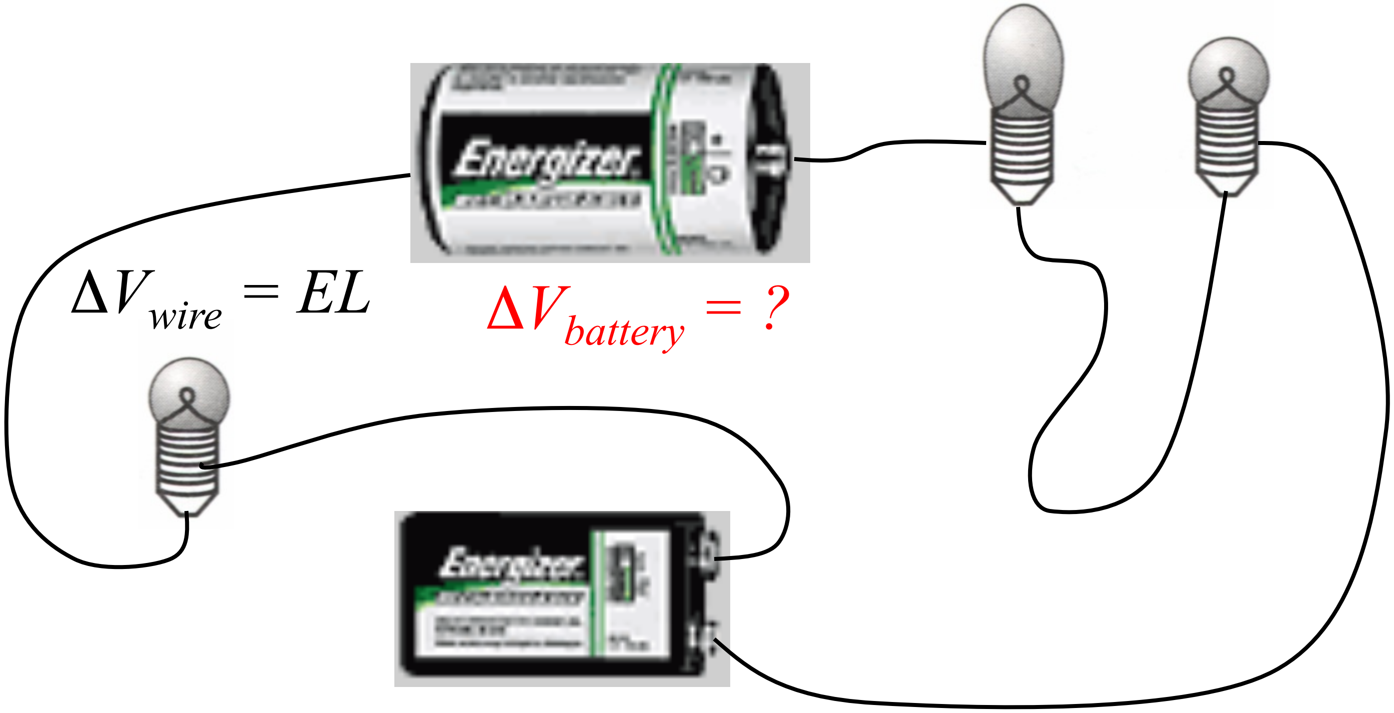
$$i = nA\bar{v} = nAuE$$

$$i_{thin} = nAu_{thin}E_{thin}$$

$$i_{thick} = nAu_{thick}E_{thick}$$

$$\boxed{E_{thin} = \frac{u_{thick}}{u_{thin}} E_{thick}}$$

Energy in a Circuit

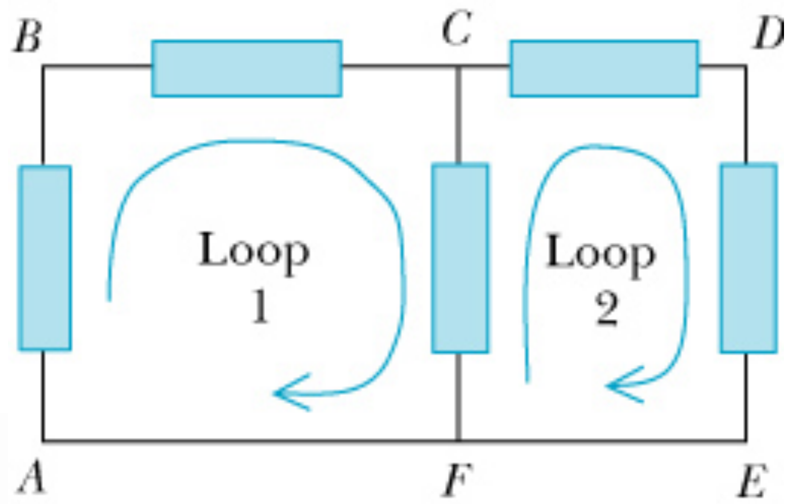


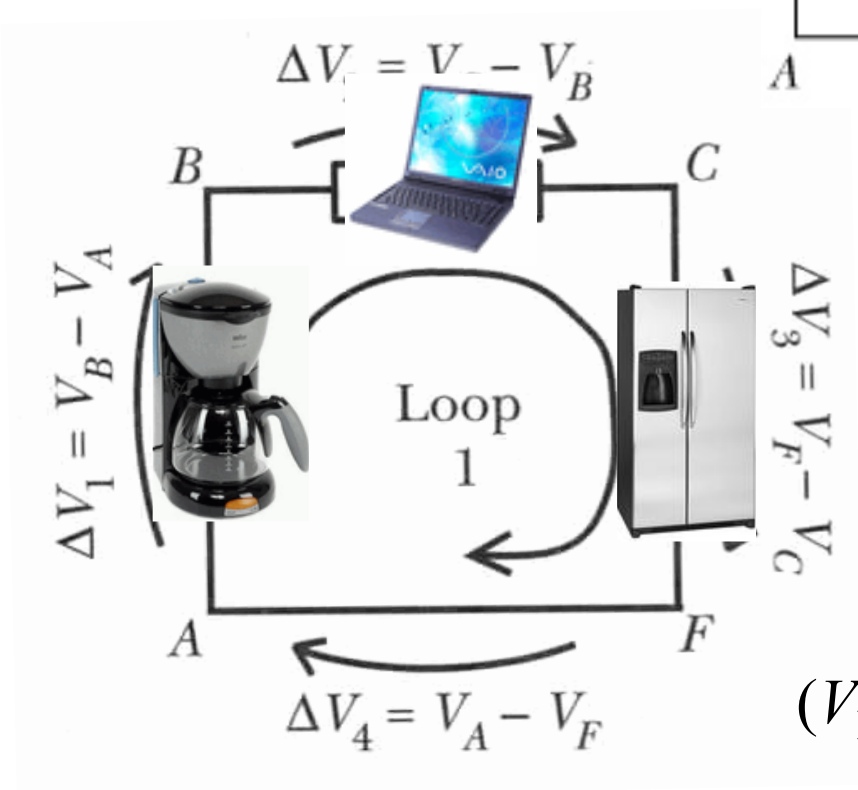
Energy conservation (the Kirchhoff loop rule [2nd law]):

$$\boxed{\Delta V_1 + \Delta V_2 + \Delta V_3 + \ldots = 0 \quad \text{along any closed path in a circuit}}$$

$\Delta V = \Delta U/q$ ← energy per unit charge

General Use of the Loop Rule

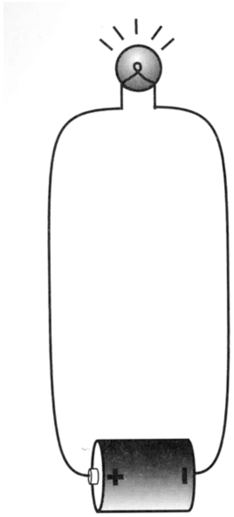




$$\Delta V_1 + \Delta V_2 + \Delta V_3 + \Delta V_4 = 0$$

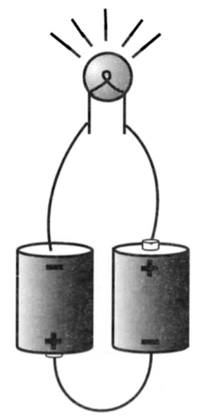
$$(V_B - V_A) + (V_C - V_B) + (V_F - V_C) + (V_A - V_F) = 0$$

Two Batteries in Series



Why light bulb is brighter with two batteries?

Two batteries in series can drive more current: Potential difference across two batteries in series is $2emf \rightarrow$ doubles electric field everywhere in the circuit $\rightarrow$ doubles drift speed $\rightarrow$ doubles current.



$$emf - EL = 0$$

$$E = \frac{emf}{L}$$

$$i = nAuE = nAu\frac{emf}{L}$$

$$P_{1batt} = eLnAu\left(\frac{emf}{L}\right)^2$$

Work per second:

$$P = (q/T)EL = ieEL$$

$$P = nAueLE^2$$

$$2emf - EL = 0$$

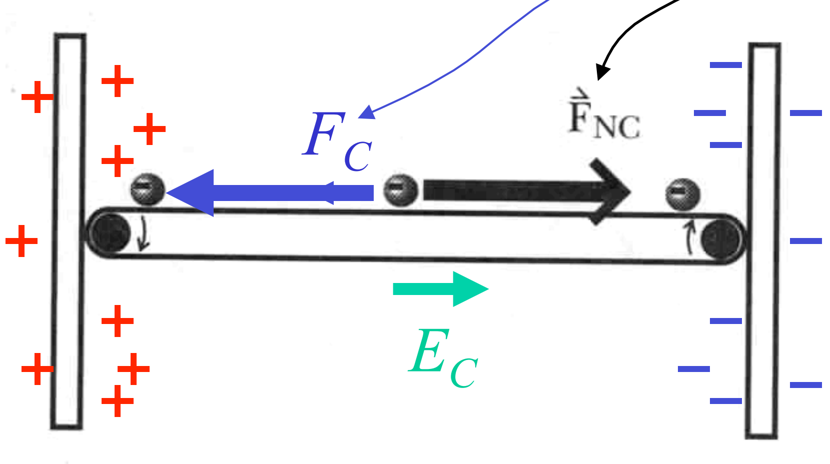
$$E = \frac{2emf}{L}$$

$$i = nAu\frac{2emf}{L}$$

$$P_{2batt} = eLnAu\left(\frac{2emf}{L}\right)^2$$

$$P_{2batt} = 4 \times P_{1batt}$$

Potential Difference Across the Battery



Coulomb force on each *e*

non-Coulomb force on each *e*

1. $a=F_{NC}/m$
2. $F_C = eE_C \longrightarrow E_C = \dfrac{F_C}{e}$
3. $F_C = F_{NC}$

$$\left|\Delta V_{batt}\right| = E_C s = \frac{F_C s}{e} = \frac{F_{NC} s}{e}$$

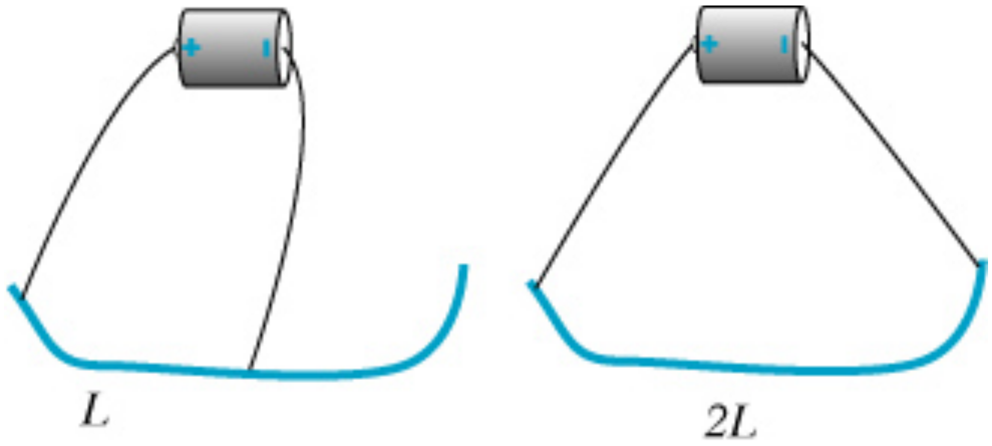
Energy input per unit charge
emf – electromotive force

The function of a battery is to produce and maintain a charge separation.

The *emf* is measured in Volts, but it is not a potential difference!
The *emf* is the energy input per unit charge.

chemical, nuclear, gravitational…

Twice the Length



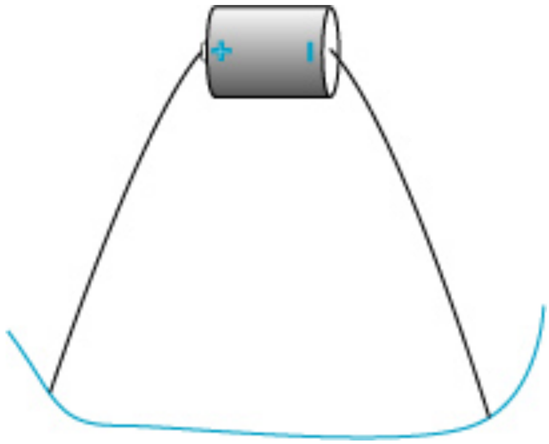
Nichrome wire (resistive)

Quantitative measurement of current with a compass

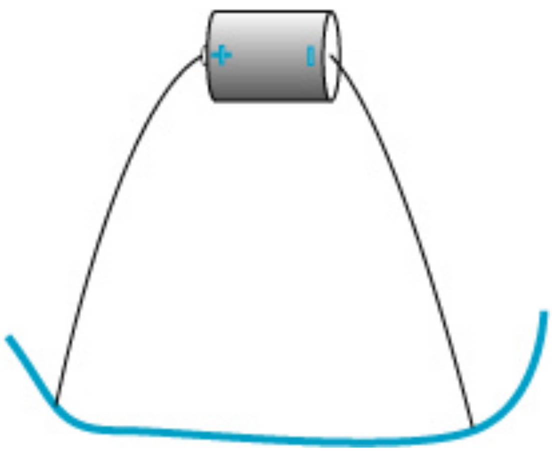
$$i = nAuE = nAu\frac{\Delta V}{L} \longrightarrow i_{2L} = nAu\frac{\Delta V}{2L} = \frac{1}{2}i_L$$

Current is halved when increasing the length of the wire by a factor of 2.

Doubling the Cross-Sectional Area



$$i_A = nAu|E|$$

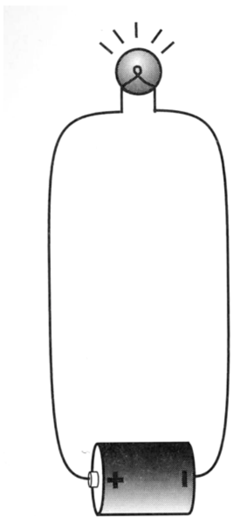


$$i_{2A} = n(2A)u|E| = 2i_A$$

If A doubles, the current doubles.

Nichrome wire

Two Batteries in Series



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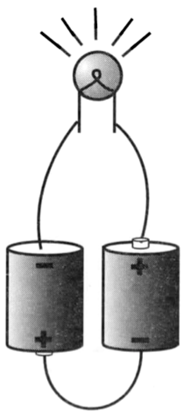

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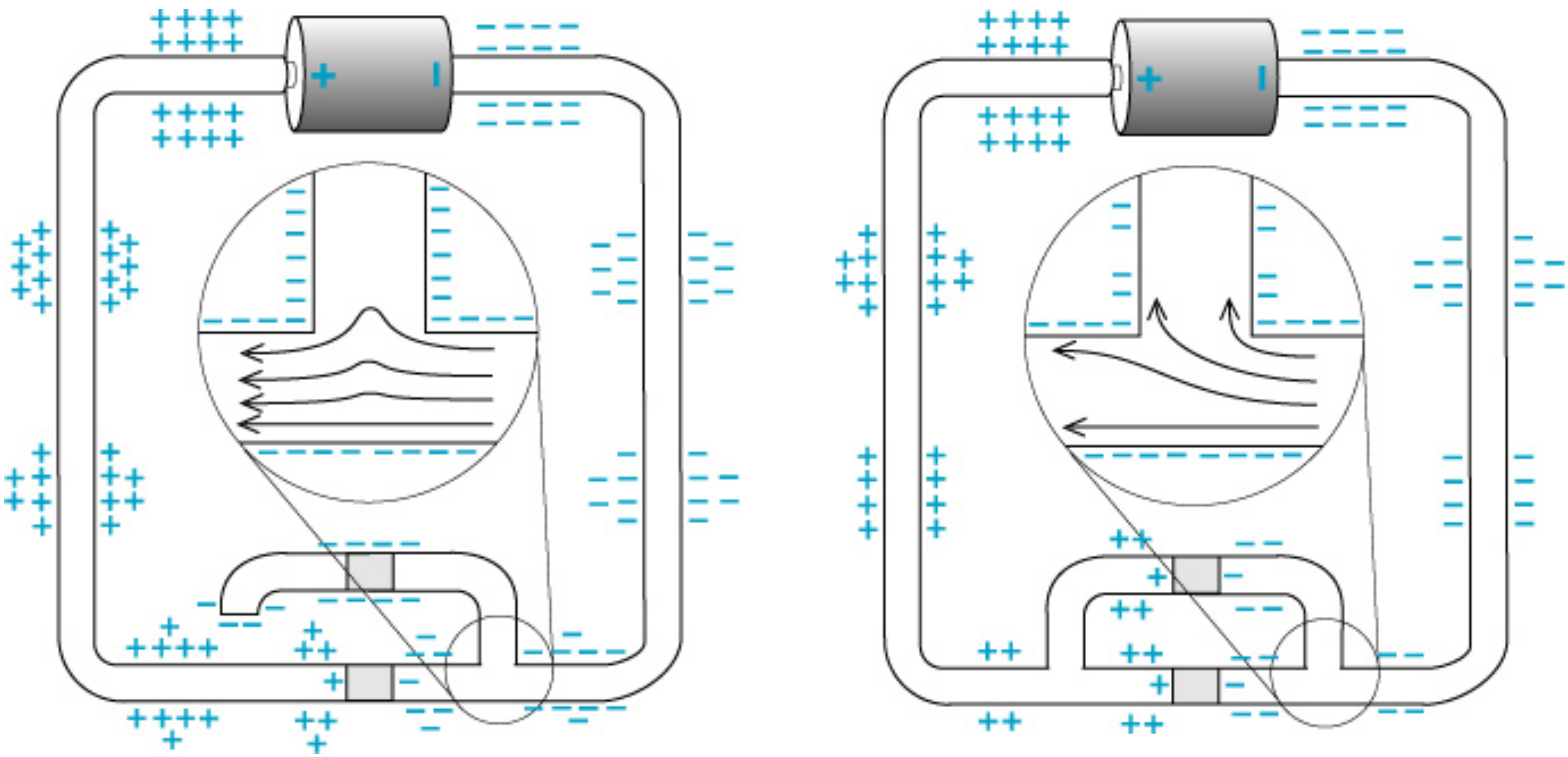
How Do the Currents Know How to Divide?



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