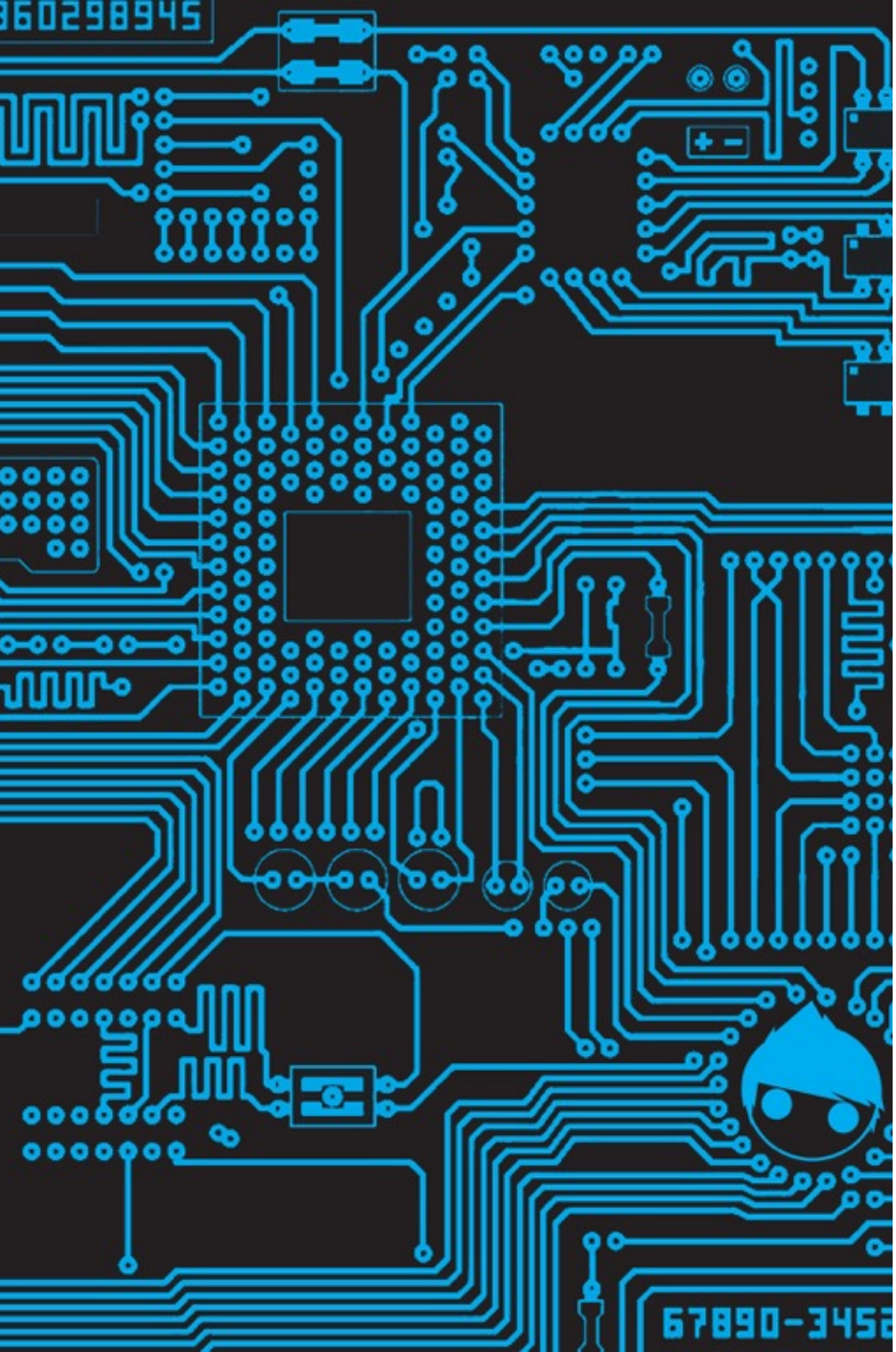
ELECTRICITY & CIRCUITS

"Electricity, the peril the wind sings to in the wires on a gray day."
— Janet Frame

LIGHTNING, PART 2

- *"Electricity is really just organized lightning" — George Carlin*
- Could you really power a city by harnessing the electrical power of lightning?

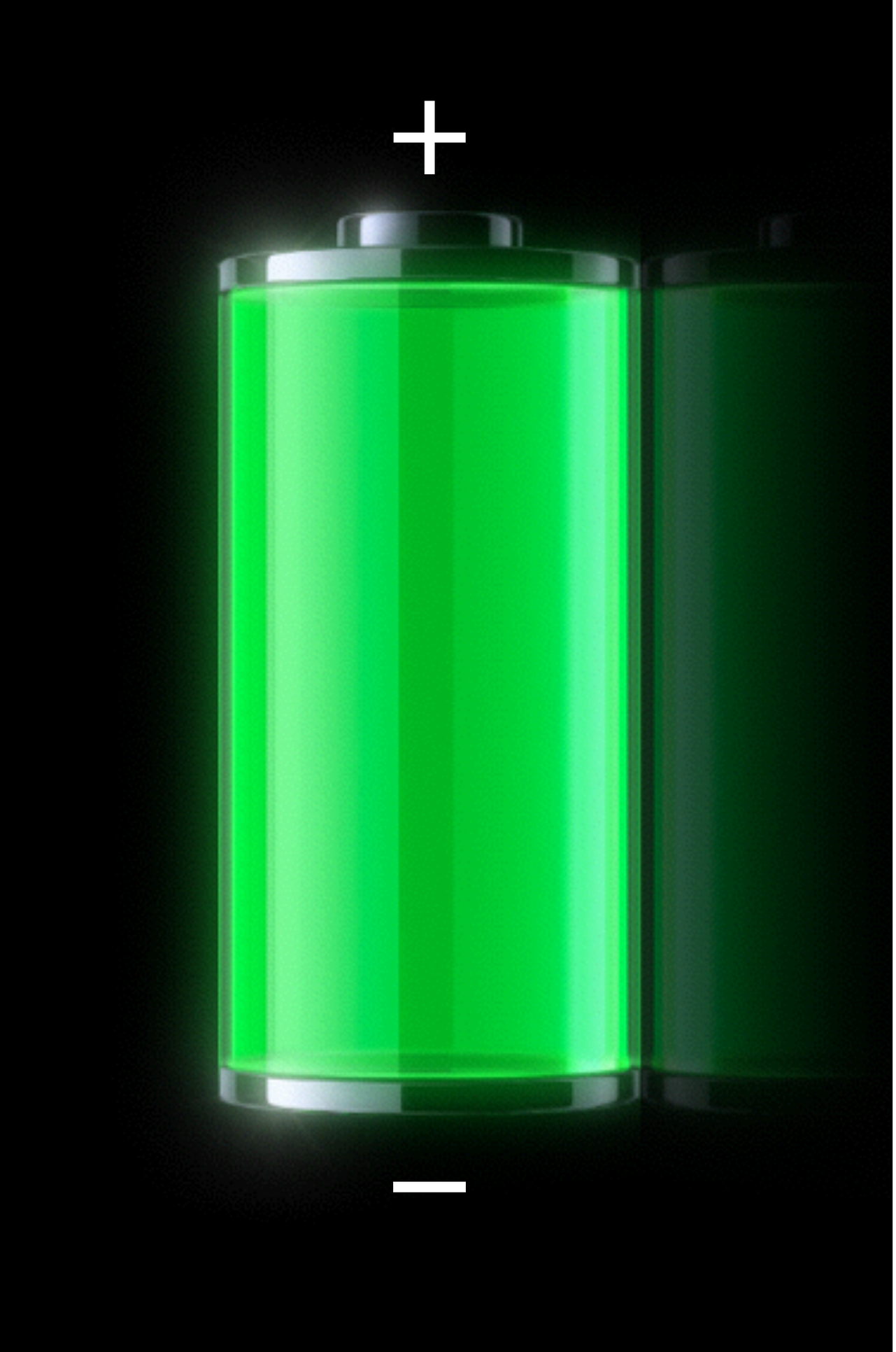


ELECTRICITY VS ELECTROSTATICS

- Electrostatics is the study of charges *at rest*
- ***Electricity*** puts those charges in motion
- In this unit, we will learn how to put charges to work in simple circuitry

ELECTRICITY

- Until 1800, electric phenomena were little more than a matter of intellectual curiosity
- Finally, in 1800, Alessandro Volta invented the electric battery — the first reliable source of electric energy
- For the first time ever, we could produce a steady flow of electric current
- This discovery transformed civilization and opened a new era run on electrical power

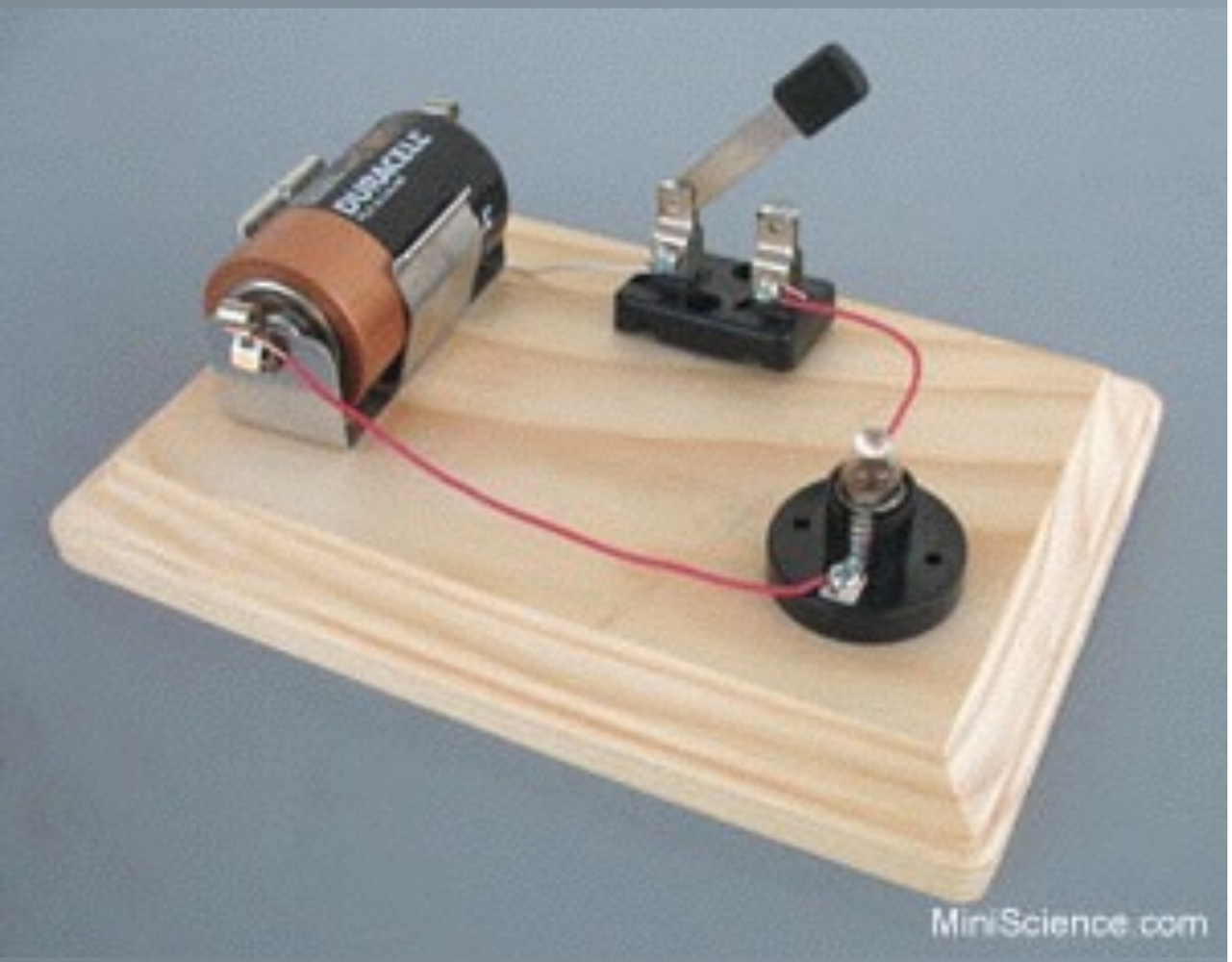


BATTERIES & VOLTAGE

- Batteries supply electric energy to a system
  - They do NOT create or even supply electric charge, they *push* charge
- Batteries use a chemical reaction to create a potential difference across its positive and negative terminals

ELECTRIC CURRENT

- ***Electric current*** is the flow of electric charge
- More accurately, it's how much charge passes through in a given amount of time
- $I = \Delta Q/\Delta t$
  - Measured in ***amperes*** (**A**)
  - 1 A = 1 C/s



EXAMPLE 1

- A steady current of 2.5 A flows in a wire for 4.0 min.

a) How much charge passed through any point in the circuit?

b) How many electrons would this be?

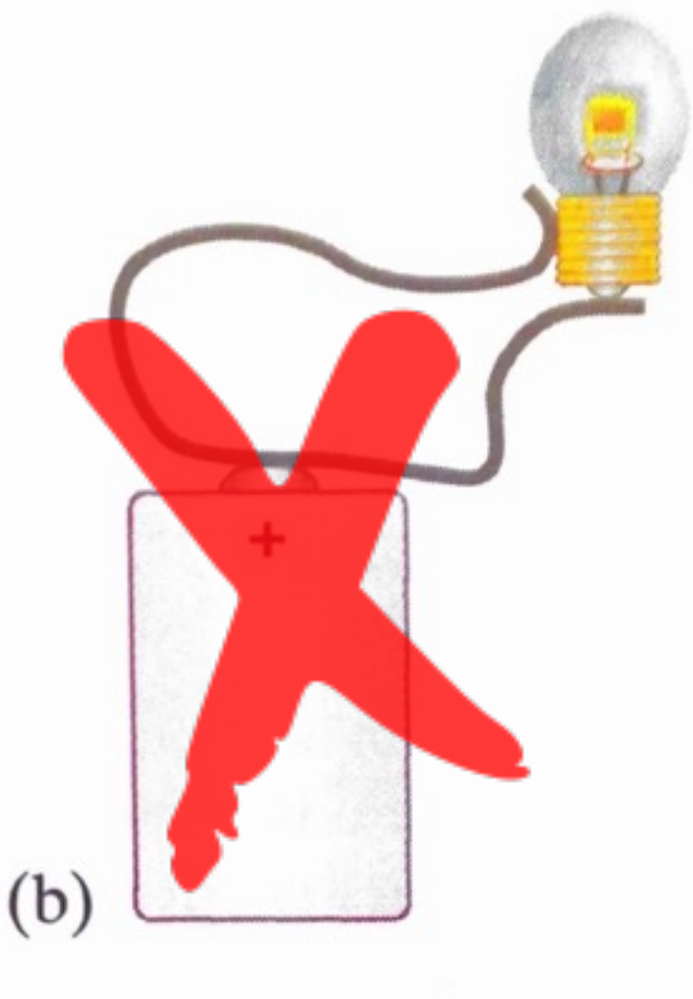
a) Ans. $\Delta Q = 600\ C$

b) Ans. 3.8×10^{21} *electrons*

SANITY CHECK

- What's wrong with each of the pictures below?

No loop for current to flow around

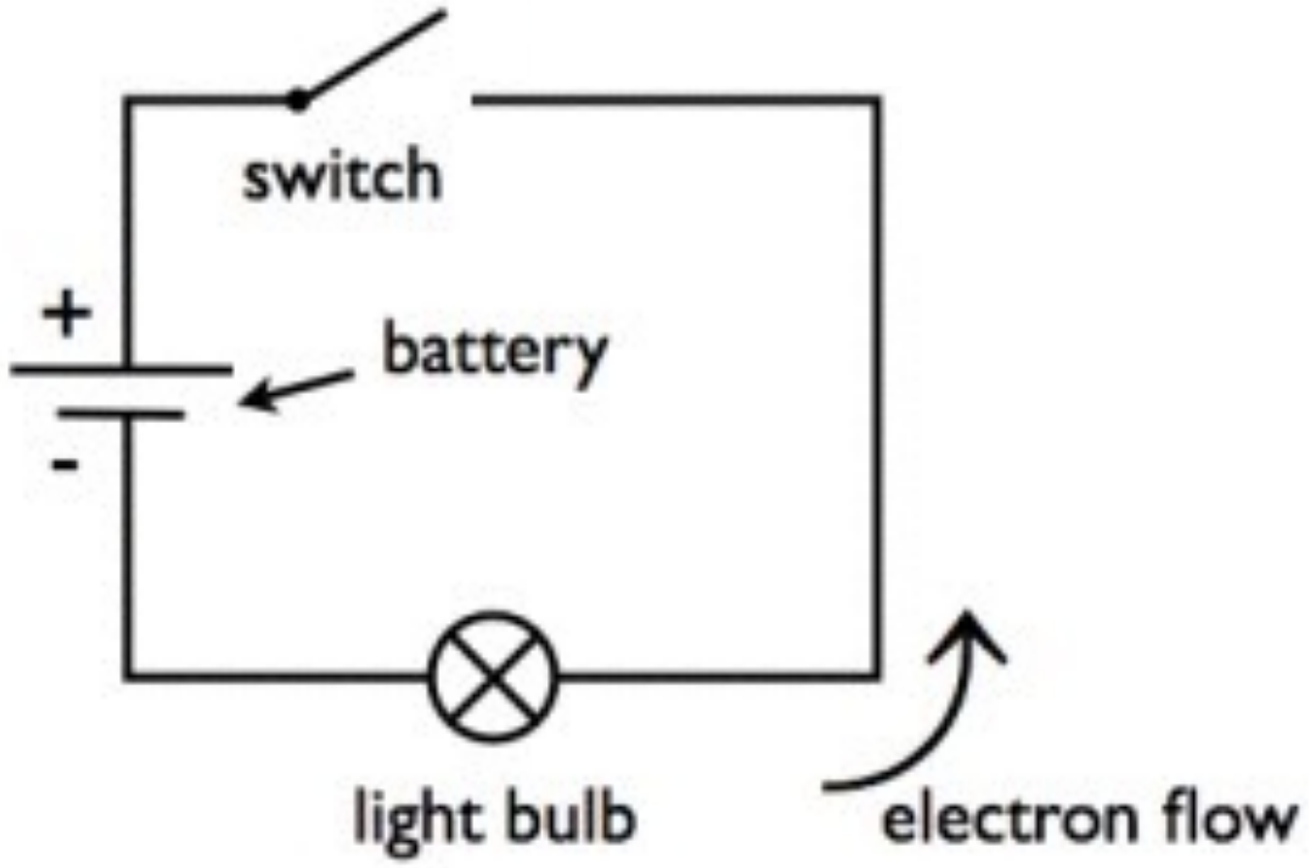


Loop, but no potential difference to push charge

All good!

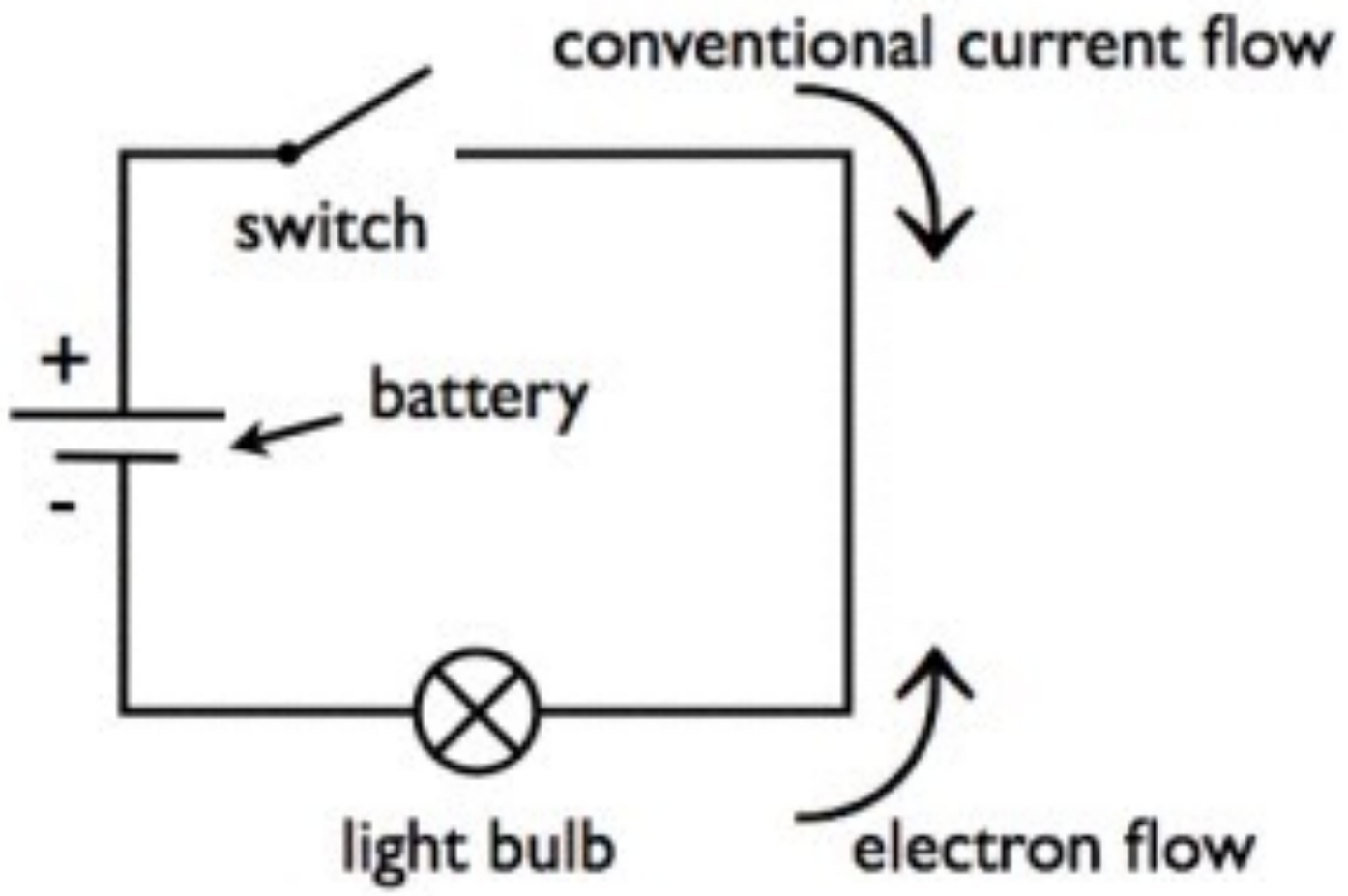
ELECTRIC CURRENT

- Conductors contain many free electrons
- So it's actually the negatively charged electrons that flow through the wire, from negative to positive



ELECTRIC CURRENT

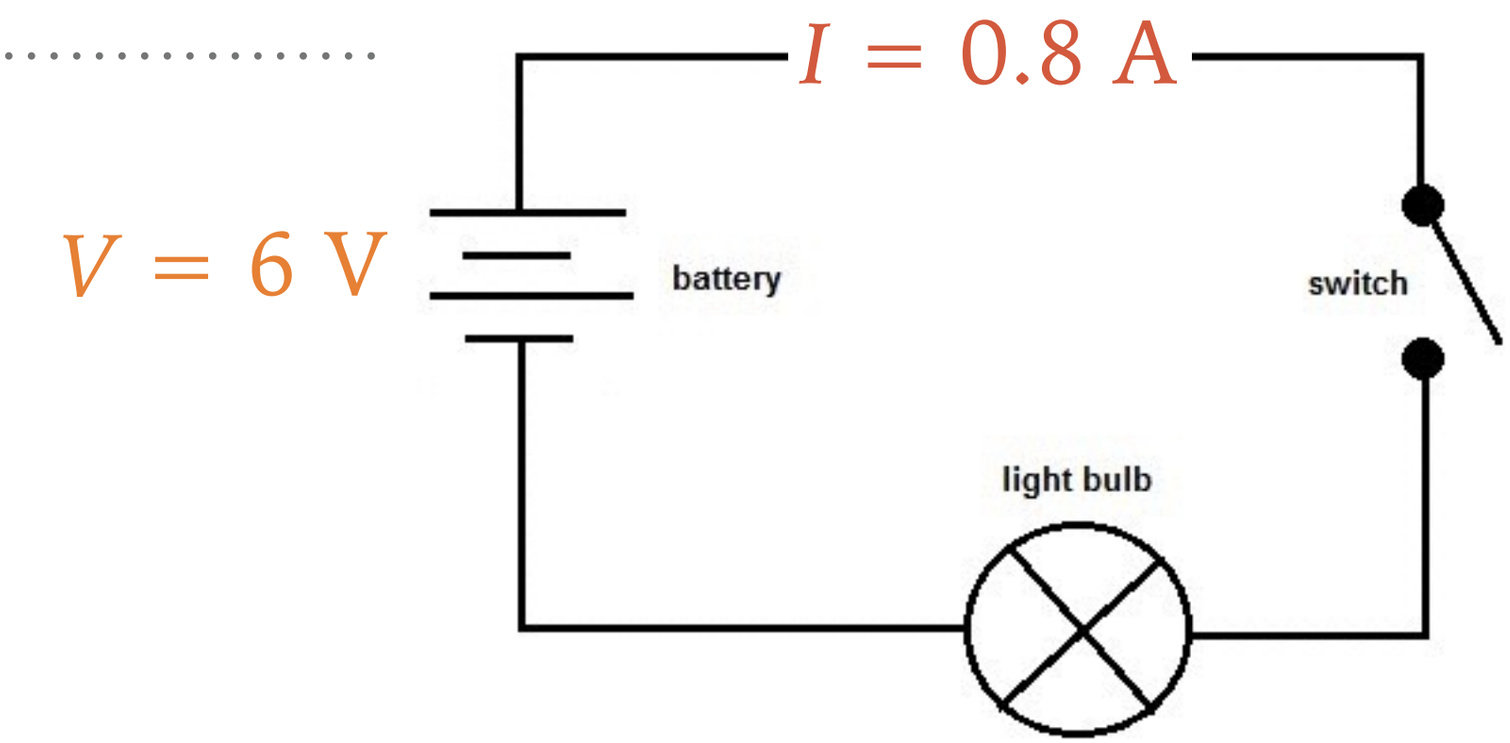
- When the conventions of positive and negative charge were invented over 200 years ago, it was thought that positive charge flowed in the wire
- Current, sometimes referred to as ***conventional current***, is therefore said to run from *positive to negative*
- The idea stuck (sorry)

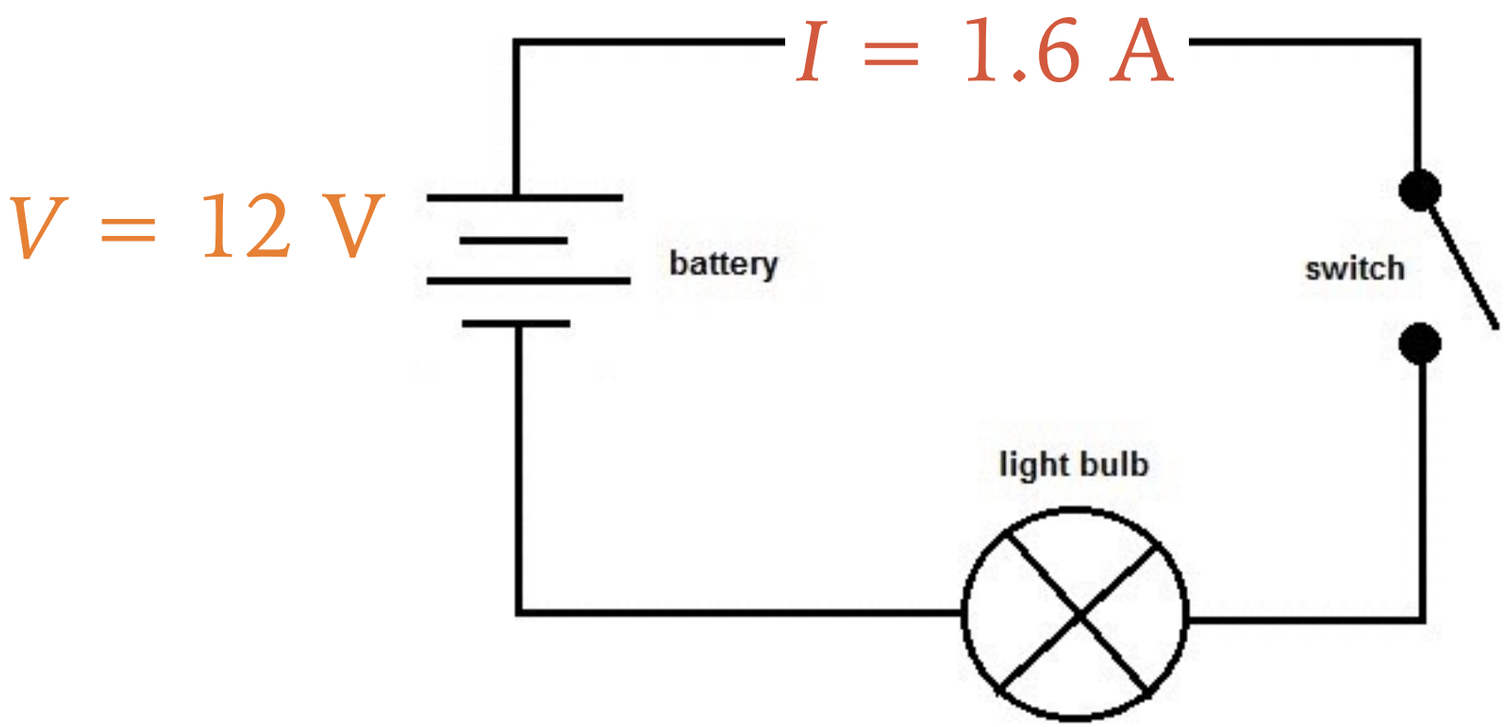


OHM'S LAW

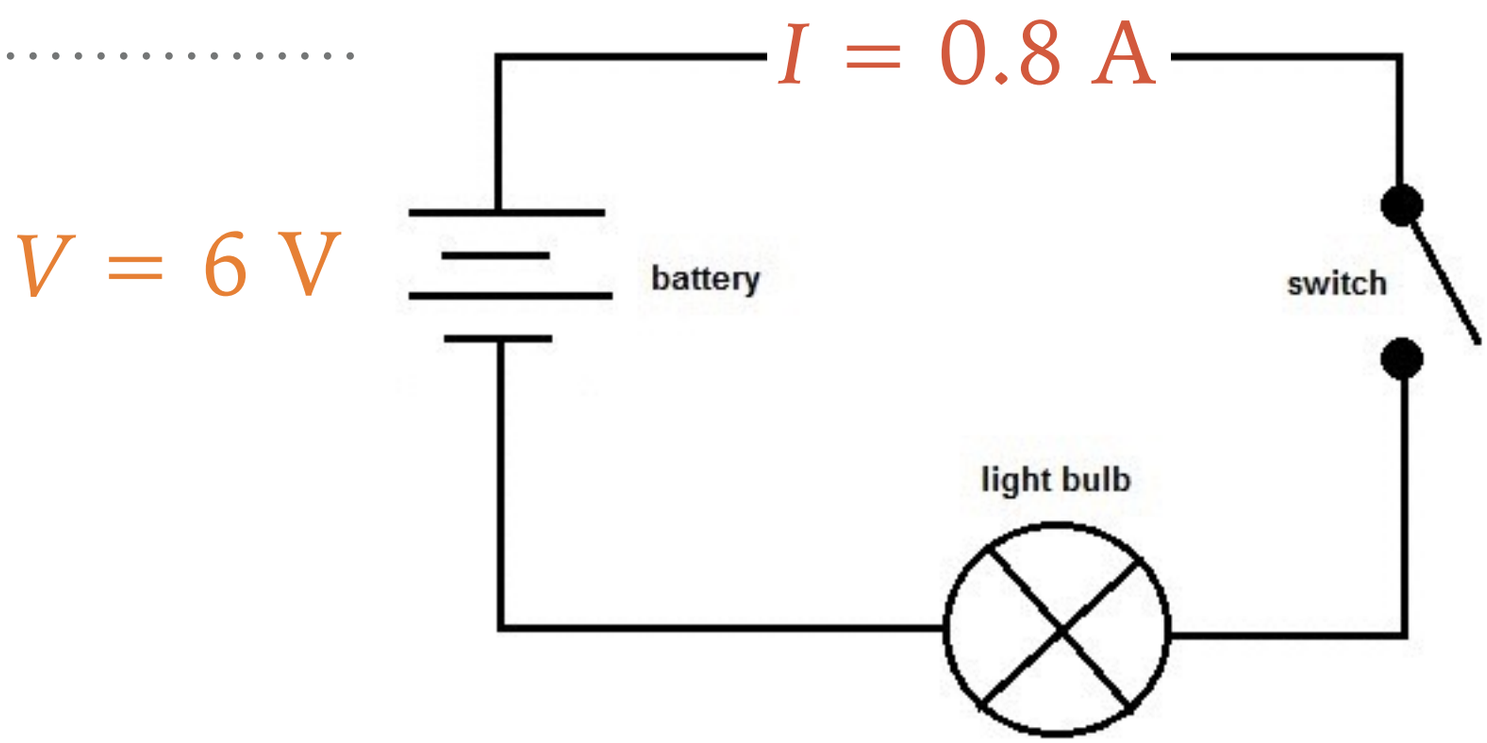
- In the early 19th Century, Georg Simon Ohm established experimentally that the current in a wire in proportional to the potential difference applied to its ends

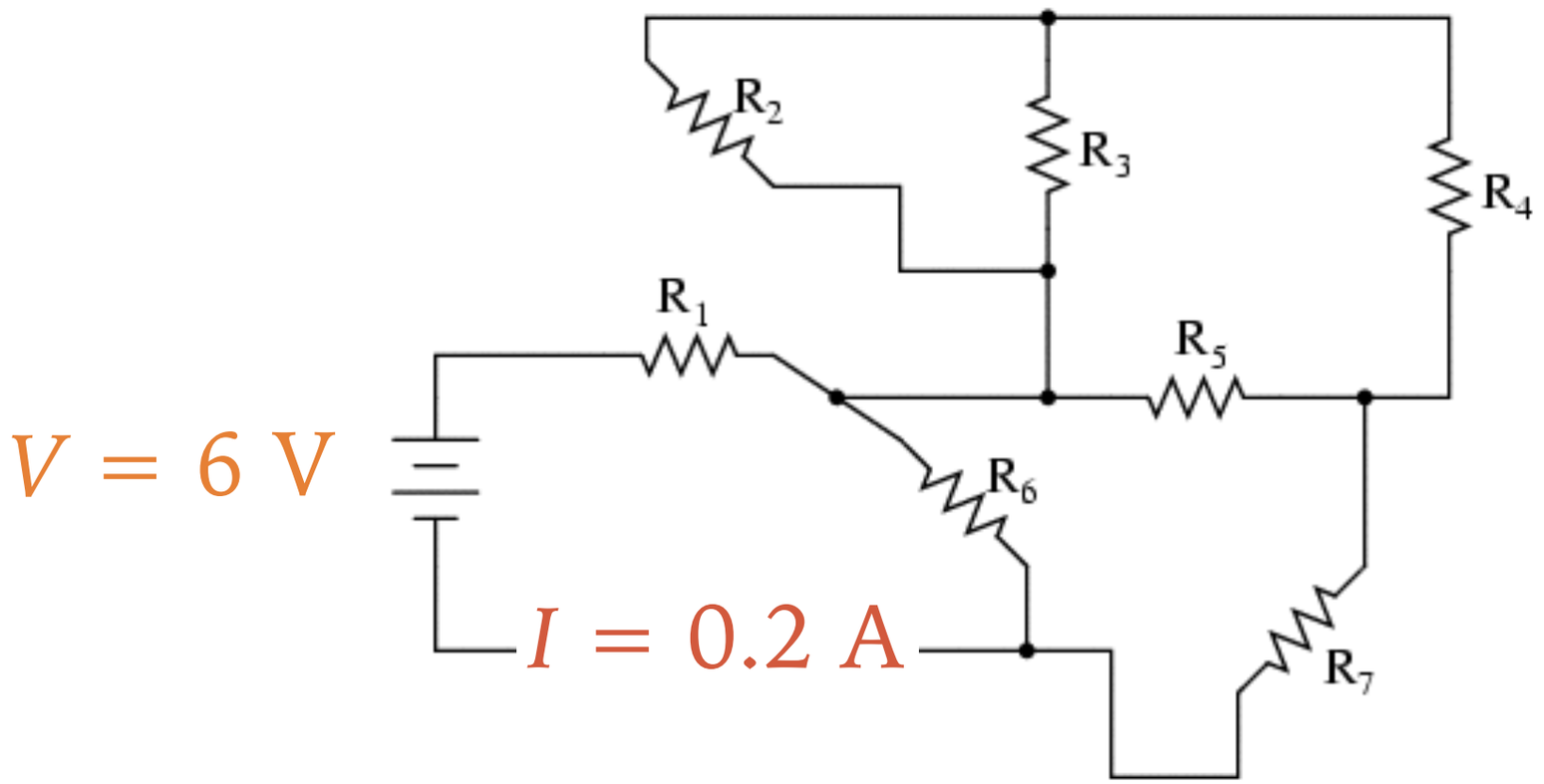
OHM'S LAW


$I = 0.8$ A
$V = 6$ V
battery
switch
light bulb

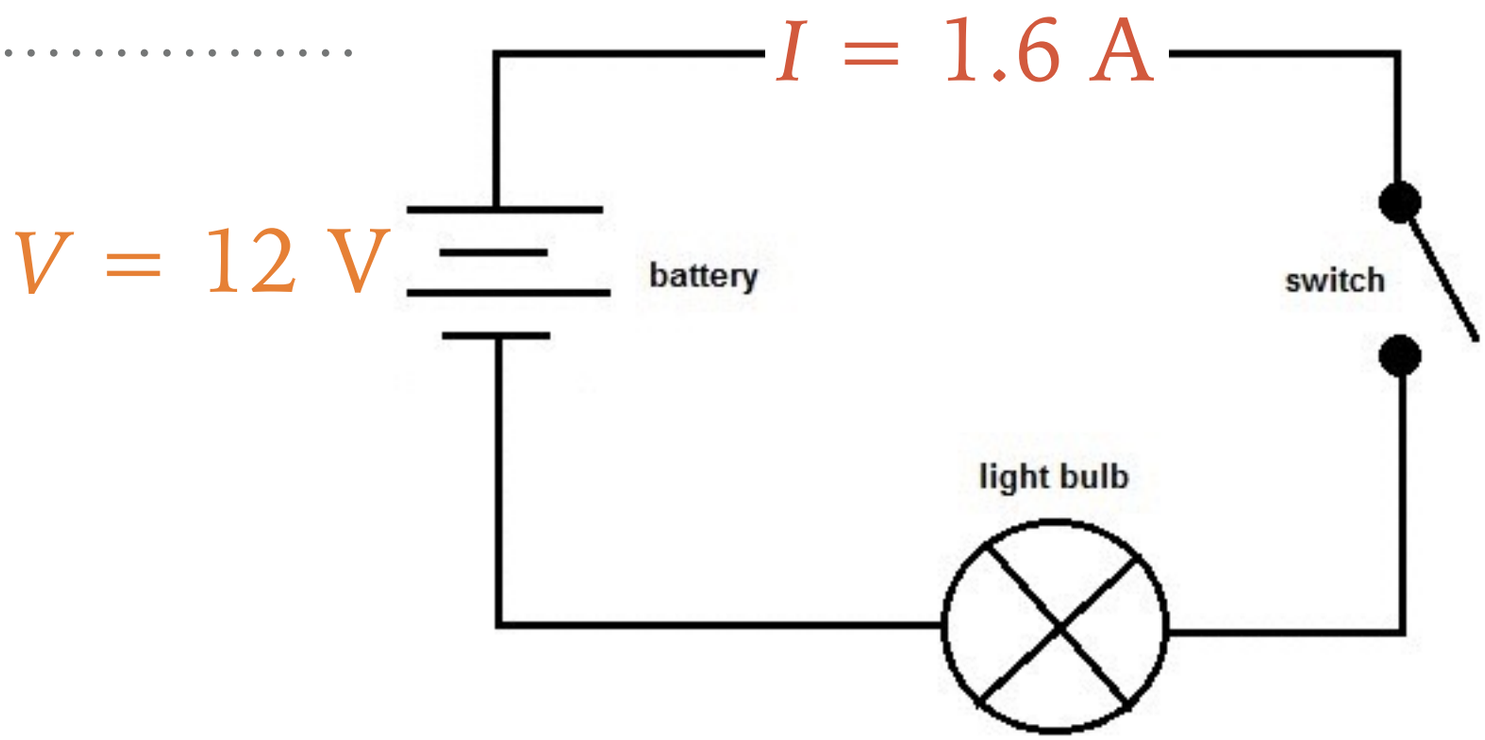

$I = 1.6$ A
$V = 12$ V
battery
switch
light bulb

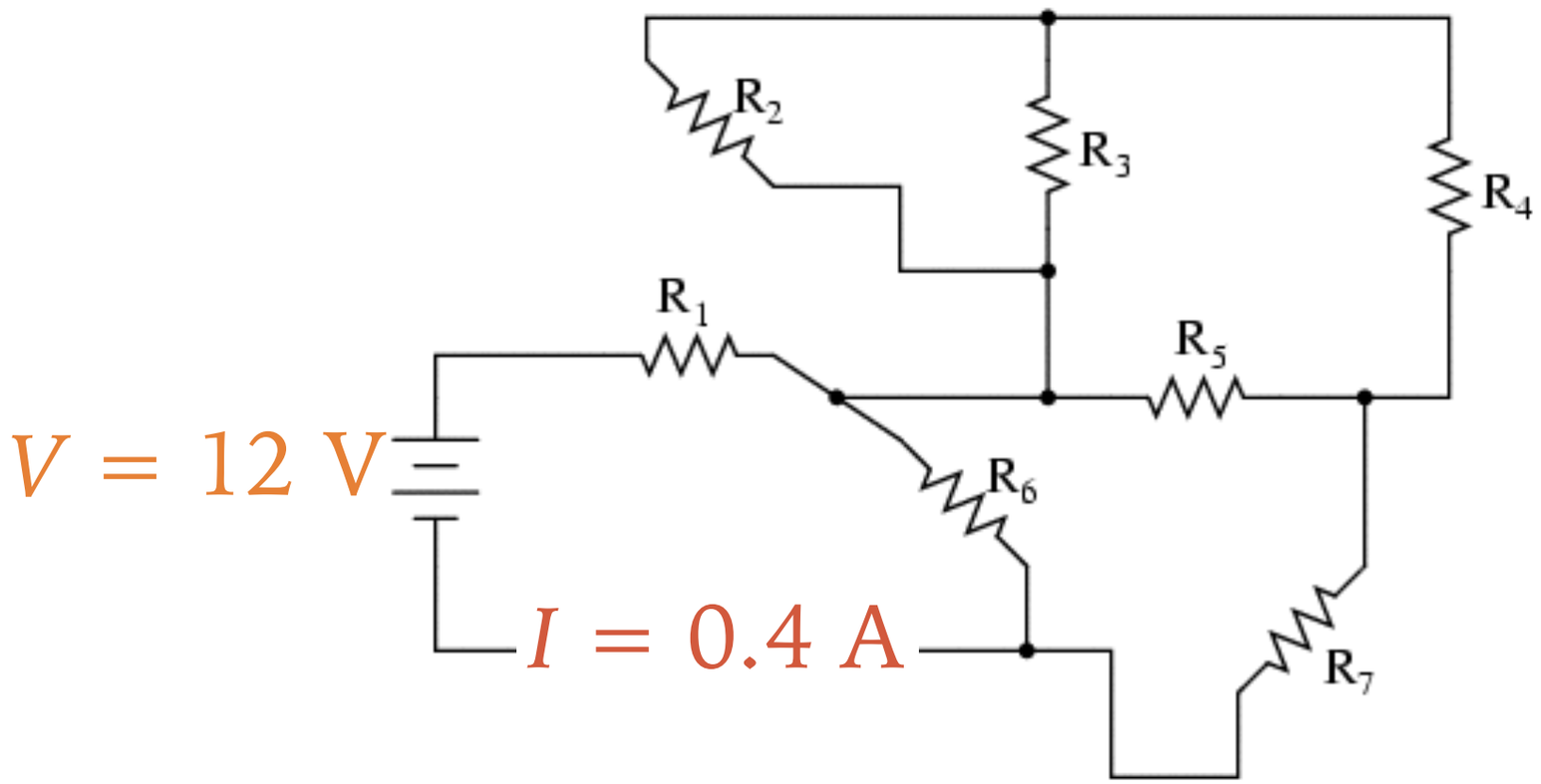
OHM'S LAW


$I = 0.8$ A
$V = 6$ V
battery
switch
light bulb

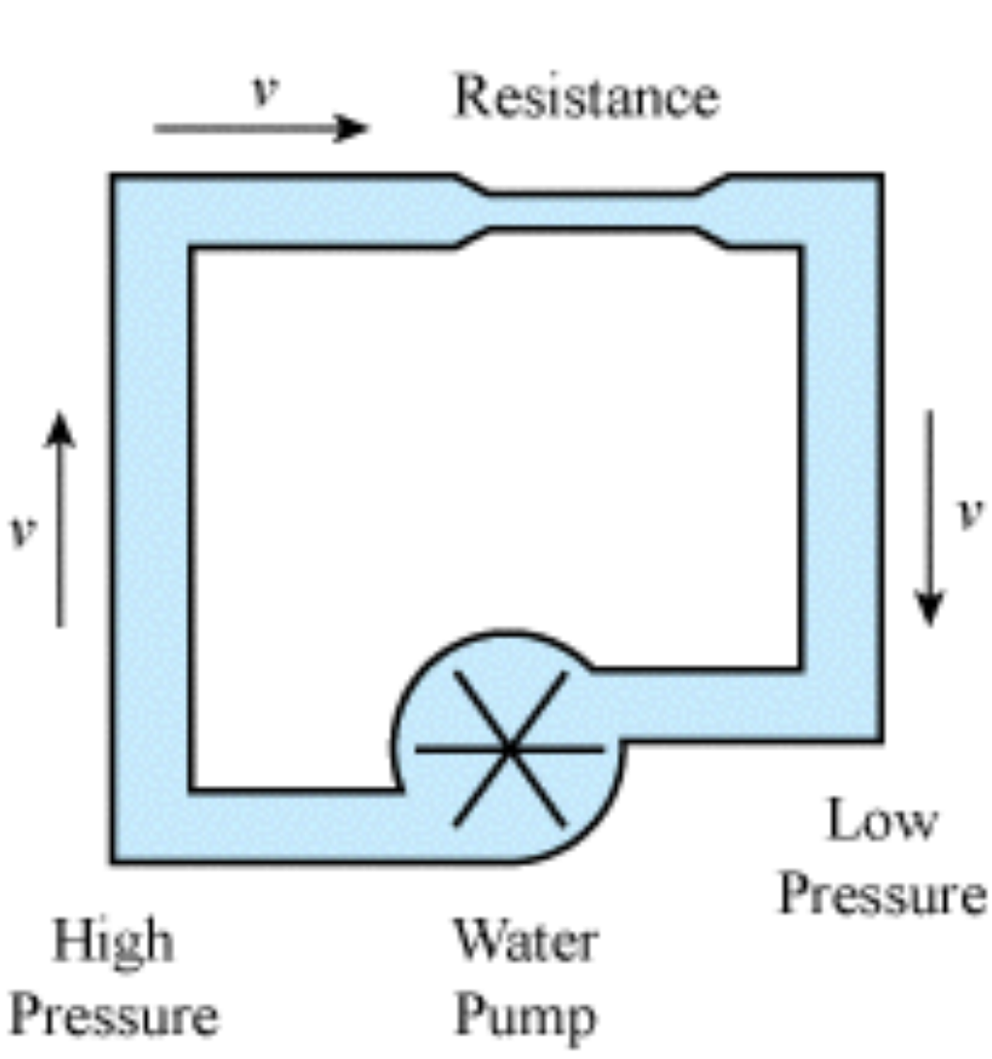

$V = 6$ V
$I = 0.2$ A
R1
R2
R3
R4
R5
R6
R7

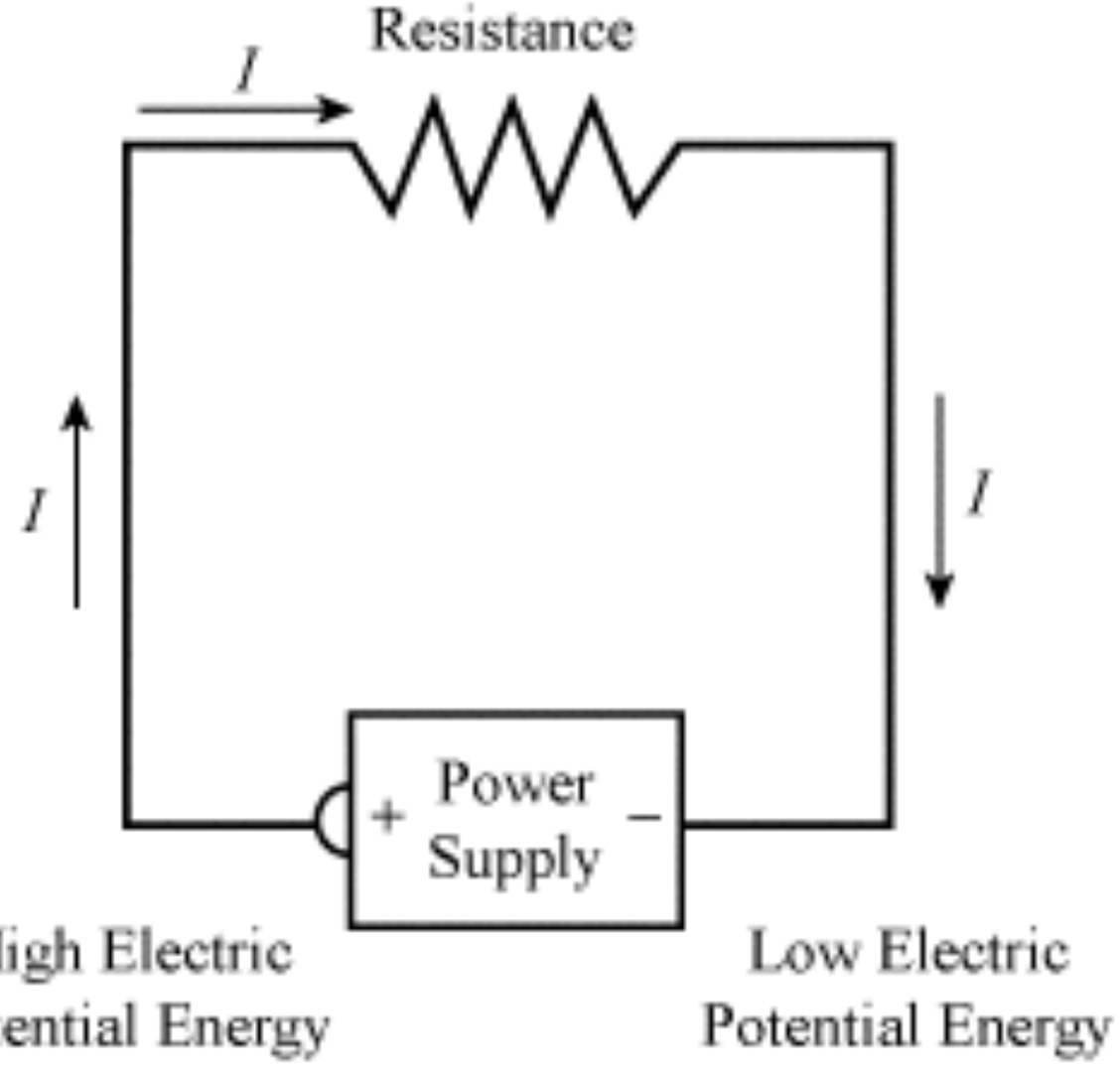
OHM'S LAW


$I = 1.6$ A
$V = 12$ V
battery
switch
light bulb

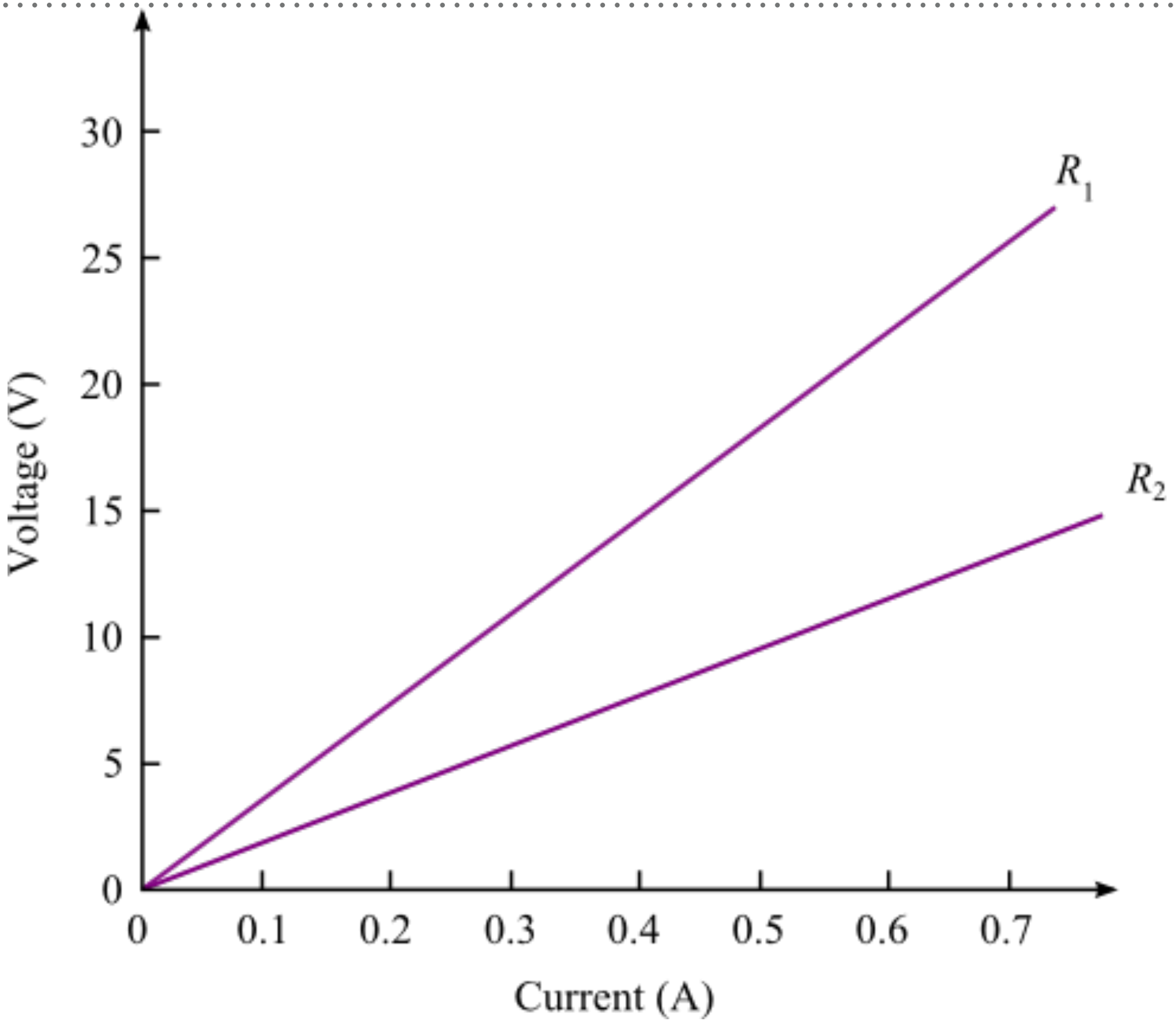

$V = 12$ V
$I = 0.4$ A
R_1
R_2
R_3
R_4
R_5
R_6
R_7

OHM'S LAW


v
Resistance
v
v
High
Pressure
Water
Pump
Low
Pressure


I
Resistance
I
I
+
Power
Supply
–
High Electric
Potential Energy
Low Electric
Potential Energy

OHM'S LAW



OHM'S LAW

- V/I = constant (based on how you build your circuit)
- That constant tells you circuit's ***resistance*** (R) to electric current
  - Resistance is measured in ***ohms*** (Ω)
- $V = IR$

EXAMPLE 2

➤ A small flashlight bulb draws 300 mA from its 1.5-V battery.

a) What is the resistance of the bulb?

b) If the voltage dropped to 1.2 V, how much would the current change?

a) Ans. $R = 5.0\ \Omega$

b) Ans. $I = 0.24\ A$

EXAMPLE 3

➤ A hair dryer draws 9.0 A when plugged into a 120-V line

a) What is its resistance?

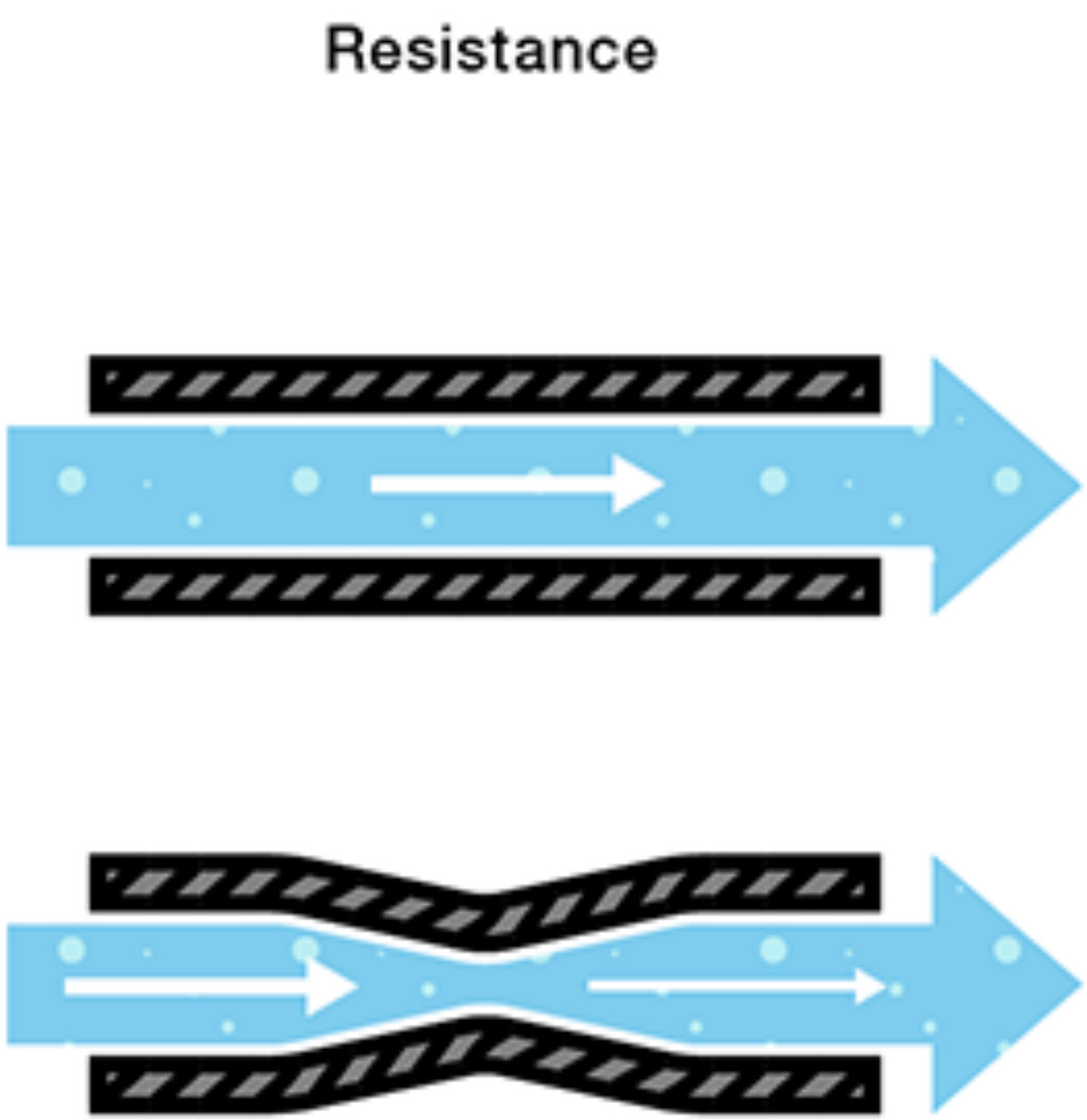
b) How much charge passes through in 15 min?

a) Ans. $R = 13.3\ \Omega$

b) Ans. $\Delta Q = 8100\ C$

OHM'S LAW

- All electronic devices offer resistance to the flow of current
- Anything that offers resistance "eats up" electric energy
  - often (read *inevitably*) by converting it to heat energy
  - sometimes in order to do work



RESISTIVITY

- Which would you expect to have more resistance?
  - Thick wire or thin wire?
  - Long wire or short wire?
  - Conductor or semiconductor?
- $R = \rho L/A$
  - ρ is the ***resistivity*** of the material
  - Measured in Ω**m**

RESISTIVITY

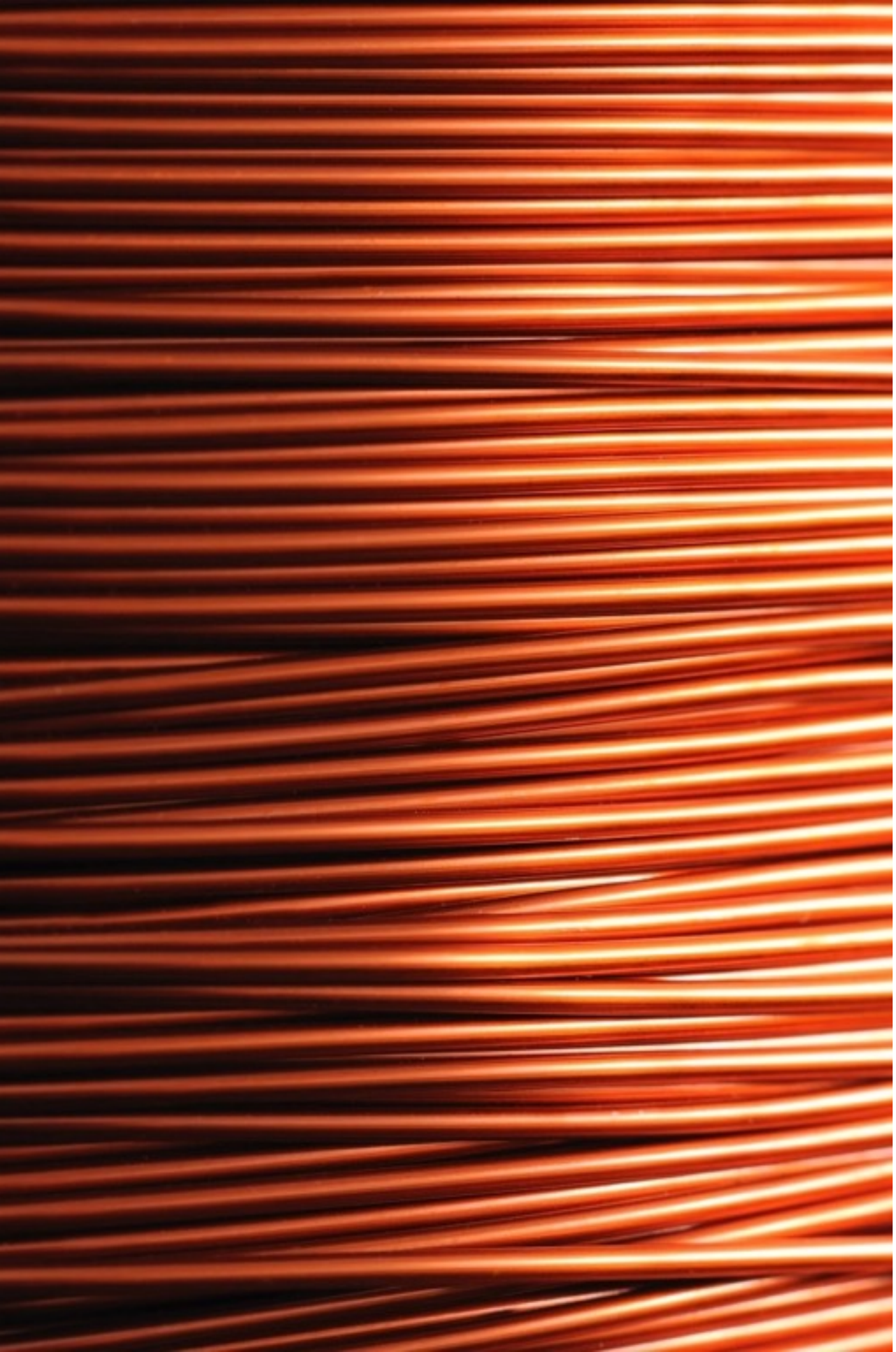
Material	Resistivity, ρ (Ωm)
Conductors	
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.44×10^{-8}
Aluminium	2.65×10^{-8}
Tungsten	5.60×10^{-8}
Iron	9.71×10^{-8}
Platinum	10.6×10^{-8}
Mercury	98.0×10^{-8}
Nichrome (alloy of Ni, Fe, Cr)	100×10^{-8}
Semiconductors	
Carbon (graphite)	$(3 - 60)\times10^{-5}$
Germanium	$(1 - 500)\times10^{-3}$
Silicon	$0.1 - 60$
Insulators	
Glass	$10^{9} - 10^{12}$
Hard rubber	$10^{13} - 10^{15}$

Material	Resistivity, ρ (Ωm)
Conductors	
Silver	1.59×10^{-8}
Copper	1.68×10^{-8}
Gold	2.44×10^{-8}
Aluminium	2.65×10^{-8}
Tungsten	5.60×10^{-8}
Iron	9.71×10^{-8}
Platinum	10.6×10^{-8}
Mercury	98.0×10^{-8}
Nichrome	100×10^{-8}
Semiconductors	
Carbon (graphite)	$(3-60)\times10^{-5}$
Germanium	$(1-500)\times10^{-3}$
Silicon	$0.1-60$
Insulators	
Glass	$10^{9}-10^{12}$
Hard rubber	$10^{13}-10^{15}$

EXAMPLE 4

➤ A 20-m-long wire is 2.1 mm thick and has a resistance of 0.14 Ω. What is the wire probably made of?

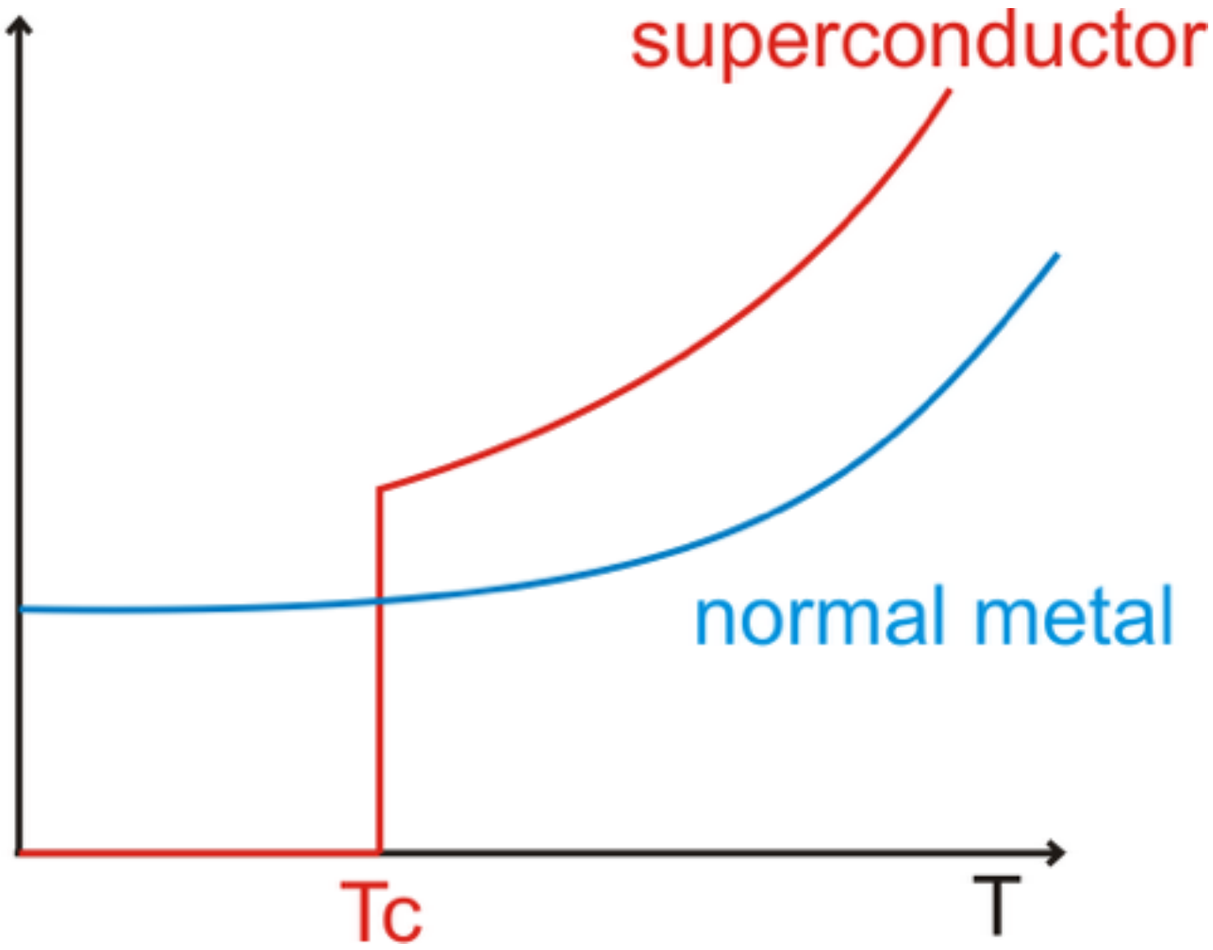
➤ *Ans. Gold*



SANITY CHECK

- A wire of resistance R is stretched uniformly until it is twice its original length. What happens to the resistance?
  - If length L doubles then the cross-sectional area A halves, so that the volume ($V = AL$) of the wire remains the same. Resistance would increase by a factor of 4.

SUPERCONDUCTORS



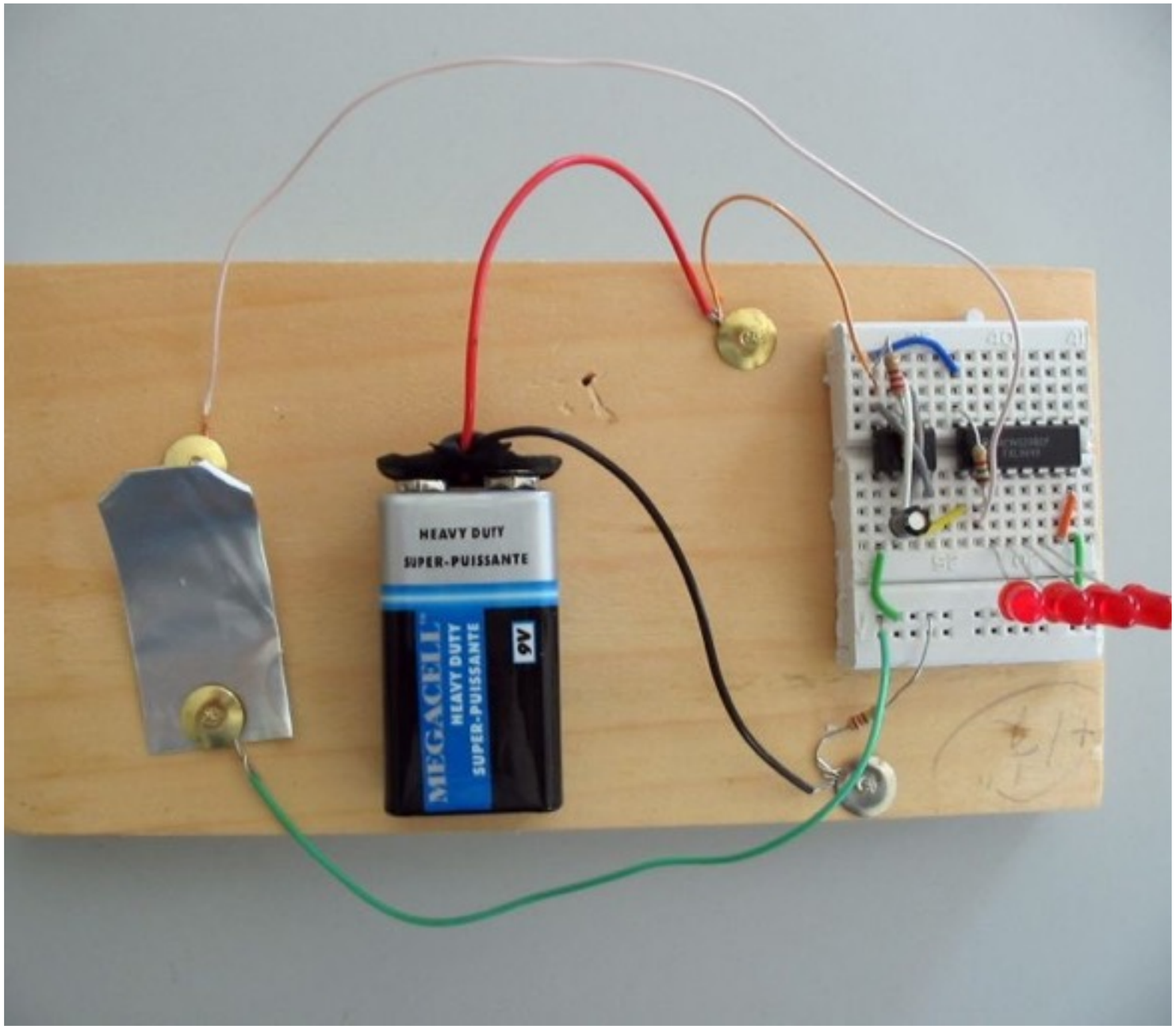
- Even the best conductors put up *some* resistance to electric current
- The resistivity of a material depends somewhat on temperature
  - Generally, resistivity increases with temperature
- Some materials, once cooled below a particular critical temperature, will offer exactly *zero* resistance
  - Materials in such a state are said to be ***superconducting***

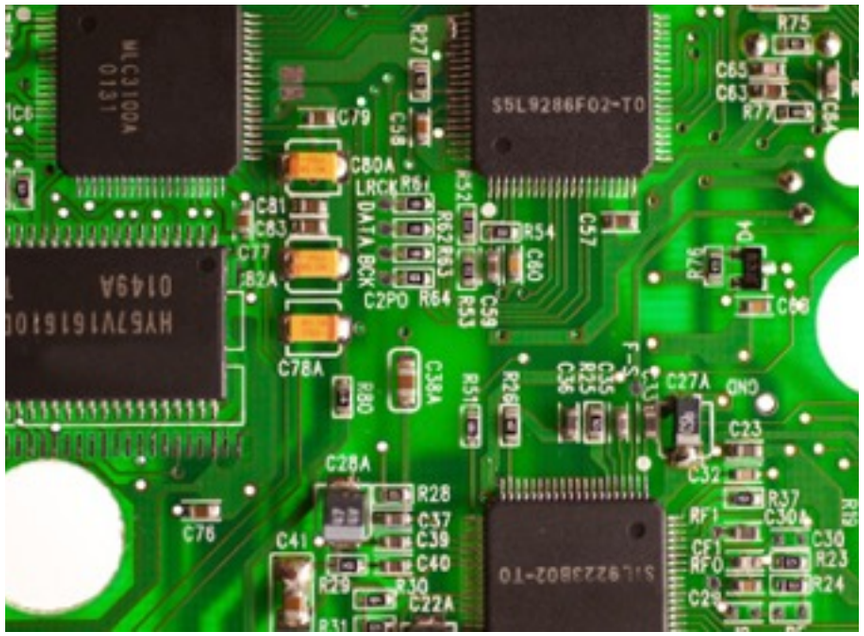
POWER

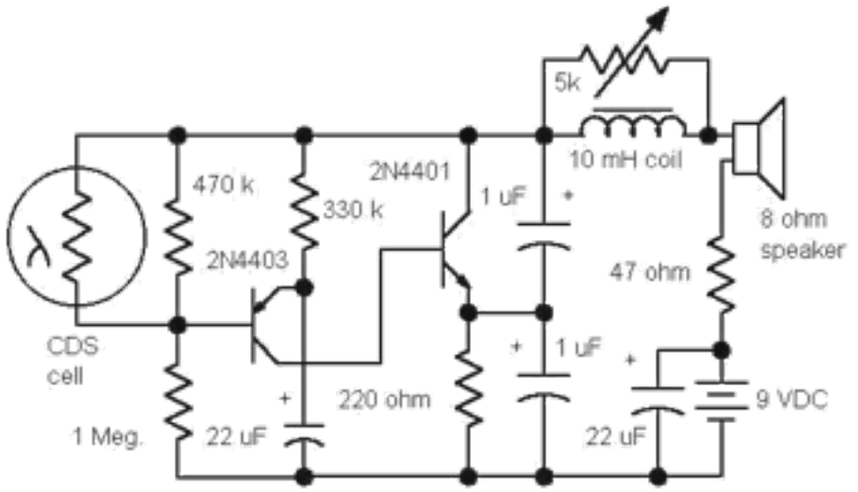
- Electric energy is useful because it can be easily transformed into other forms of energy
  - motors turn it into mechanical work
  - electric heaters, stoves, toasters, and hair dryers turn it into thermal energy
  - lightbulbs turn it into light and thermal energy
- $P = IV = I^2R = V^2/R$

EXAMPLE 5

- Calculate the resistance of a 40-W car headlight designed for 12 V
  - *Ans.* $R = 3.6\ \Omega$

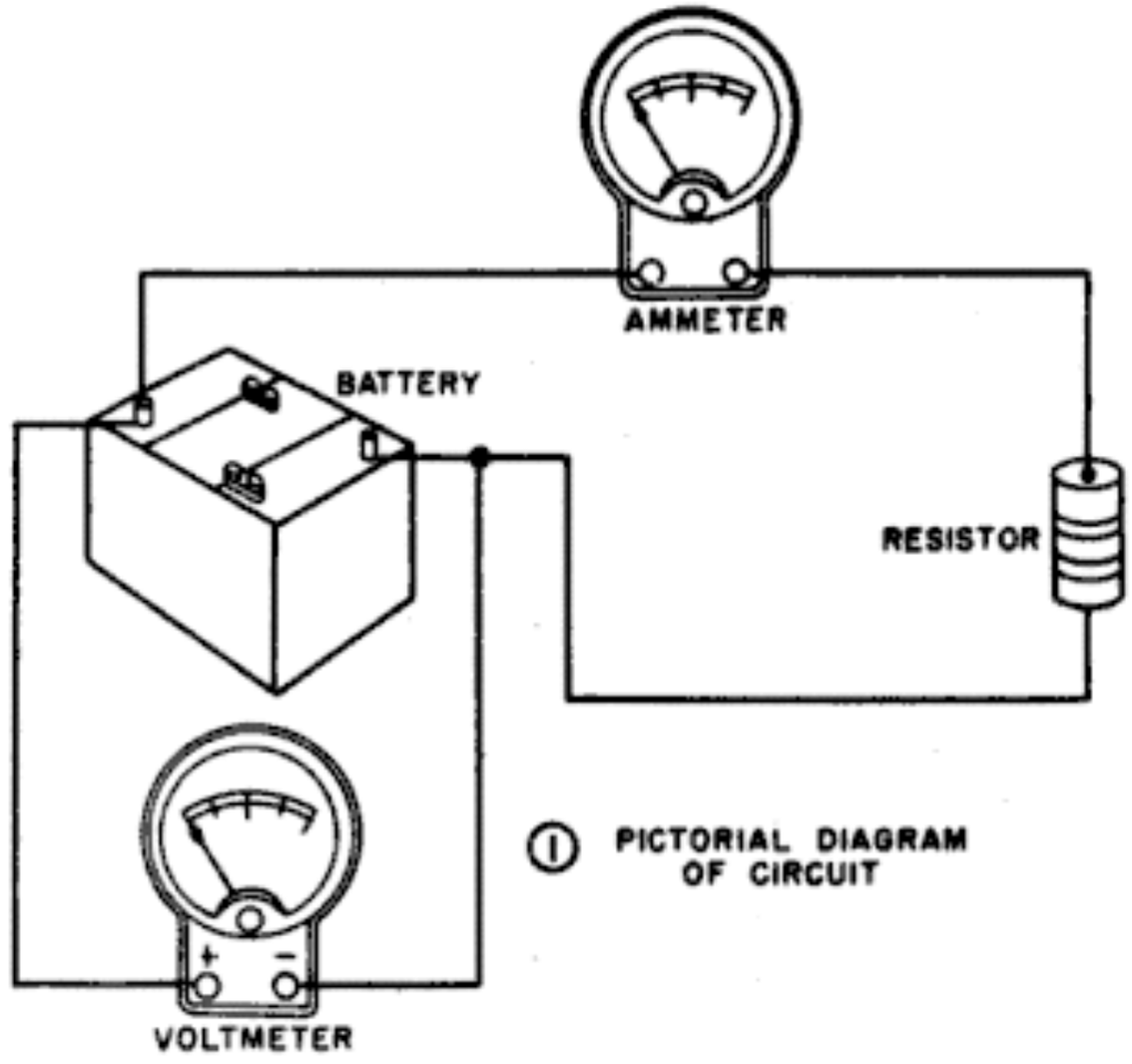




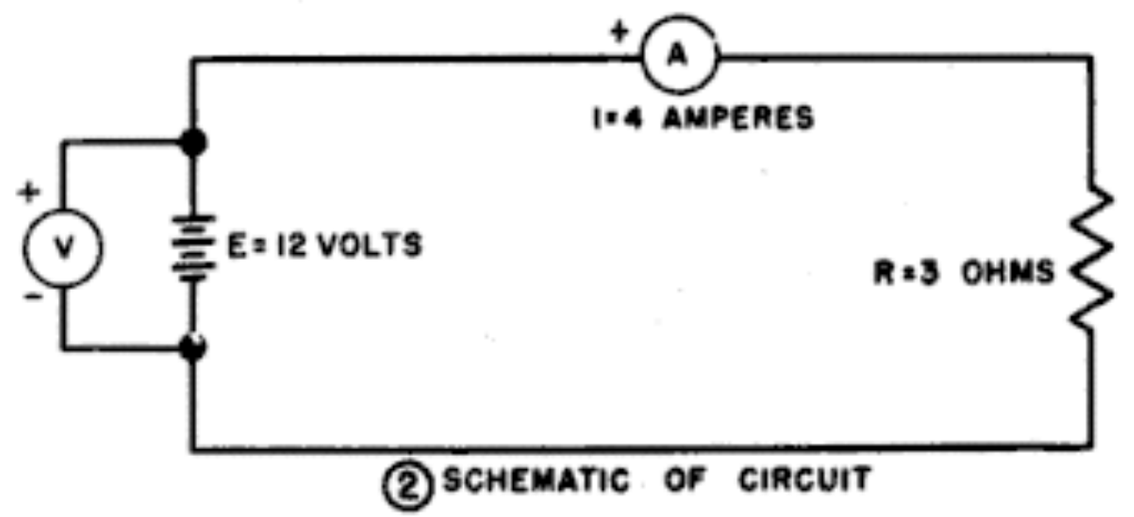


Building Circuits

CIRCUIT DIAGRAMS



① PICTORIAL DIAGRAM OF CIRCUIT

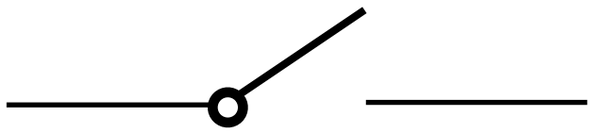


② SCHEMATIC OF CIRCUIT

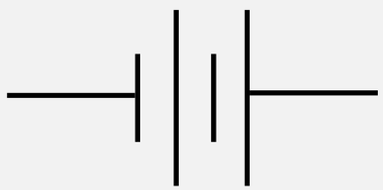
Figure 48. Diagram of a basic circuit.

CIRCUIT DIAGRAMS

Wire



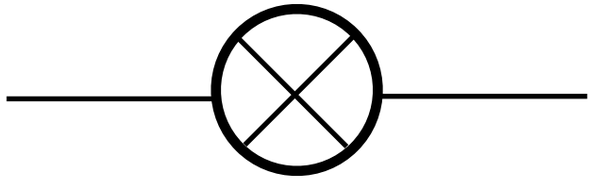
Switch



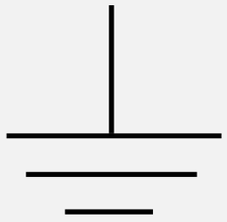
DC Battery

AC Voltage Source

Resistor

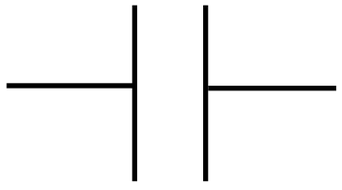


Lamp

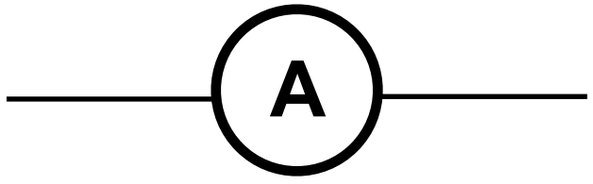


Ground

Voltmeter

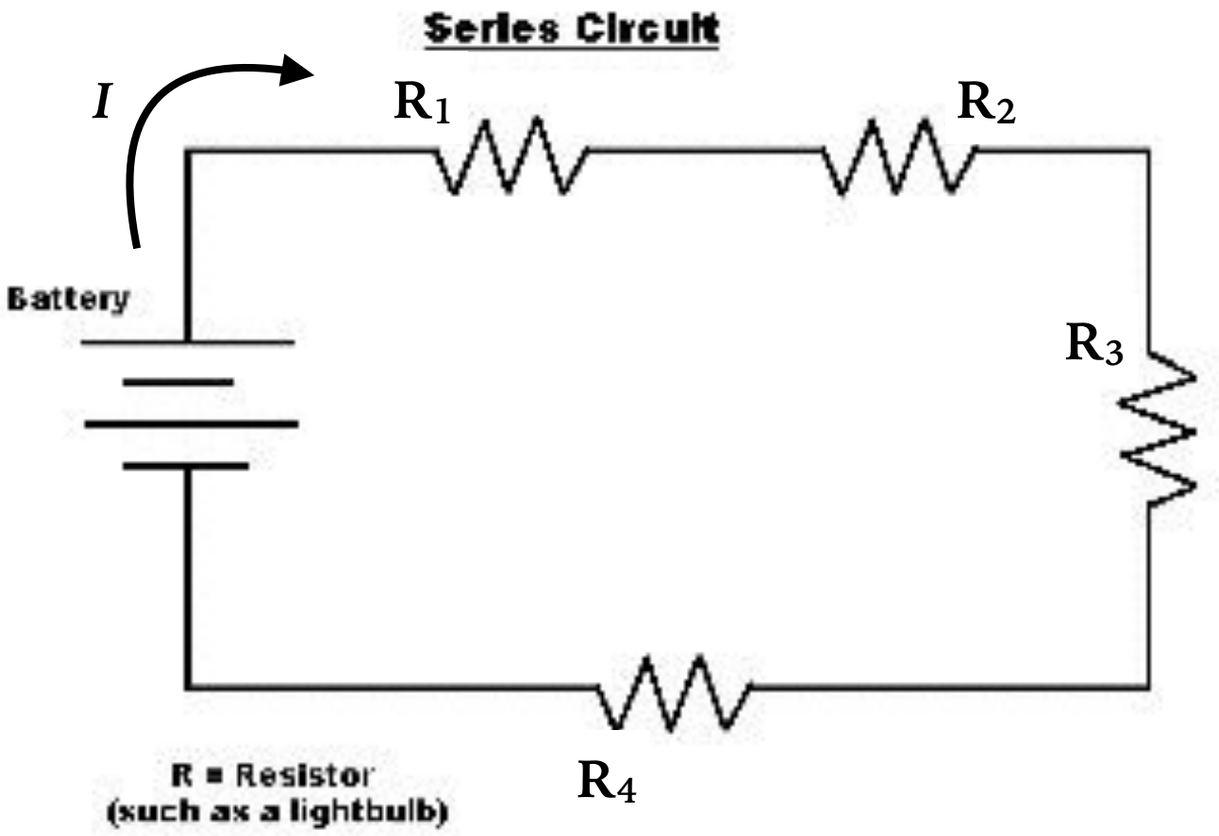


Capacitor

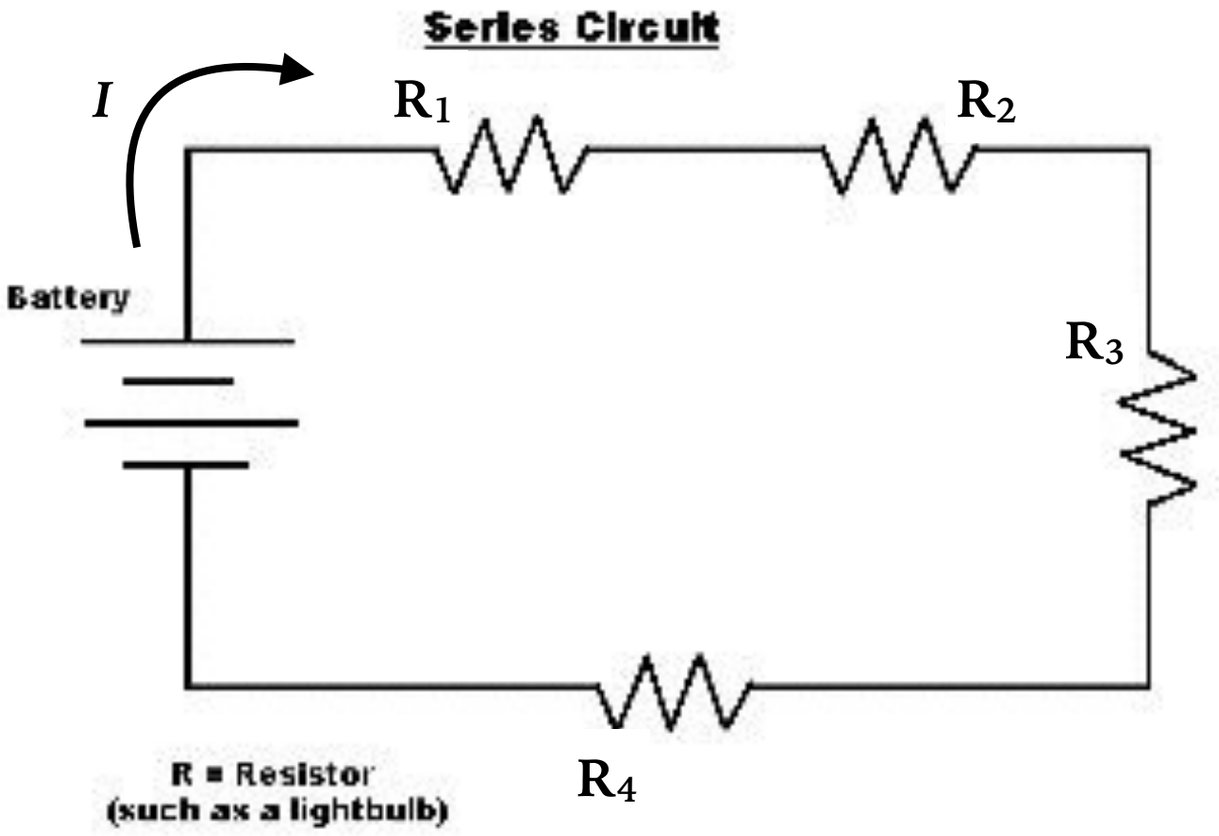


Ammeter

SERIES & PARALLEL



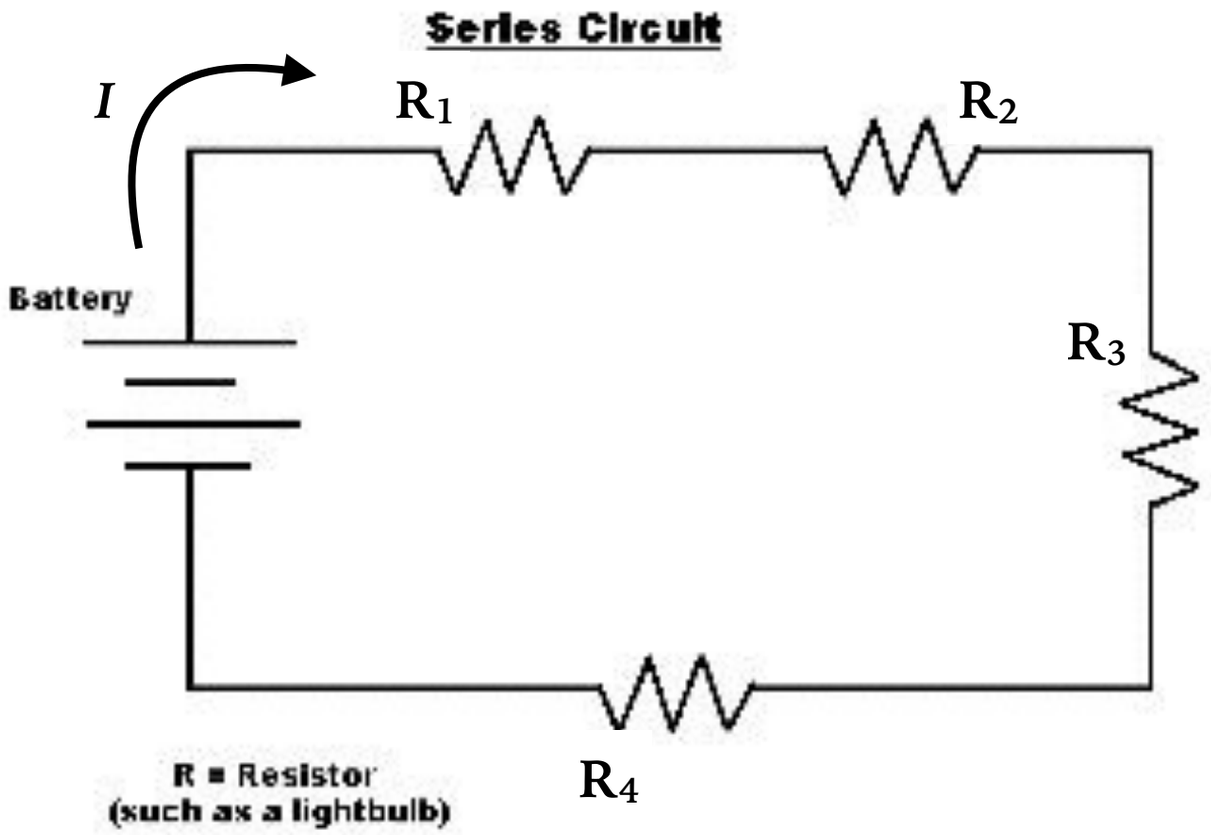
- When two or more resistors are connected end to end, they are said to be connected in ***series***
- Any charge that passes through R_1 will also pass through R_2 and then R_3, etc.
- Hence, the same current I will pass through each resistor



SERIES & PARALLEL

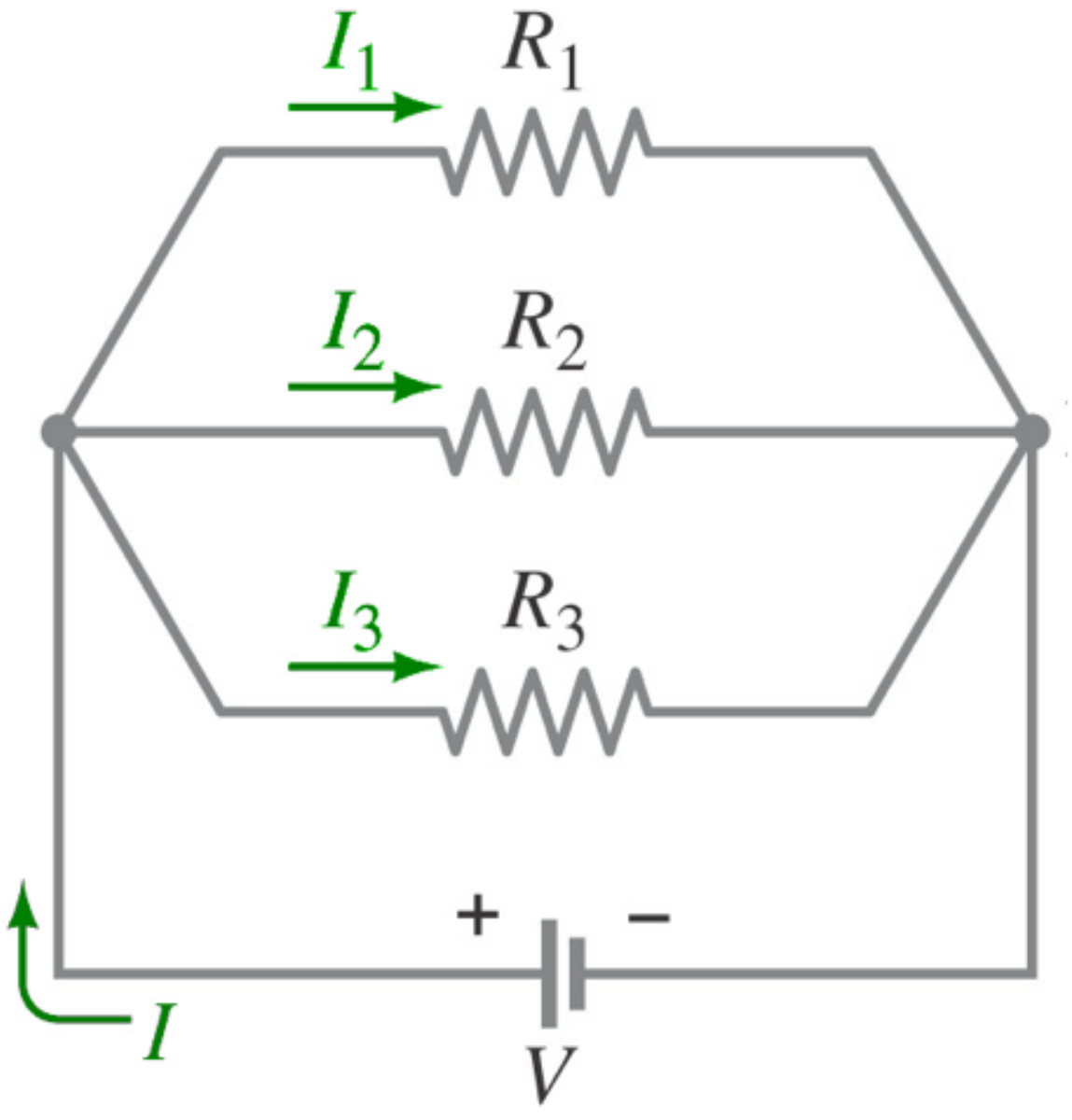
- Each resistor eats up some of the energy supplied by the battery
  - i.e. the voltage will drop across each resistor
- Drop by how much?
  - Ohm's Law tells us: $V_1 = IR_1$, $V_2 = IR_2$, $V_3 = IR_3$, etc.
- $V = V_1 + V_2 + V_3 + V_4$

SERIES & PARALLEL



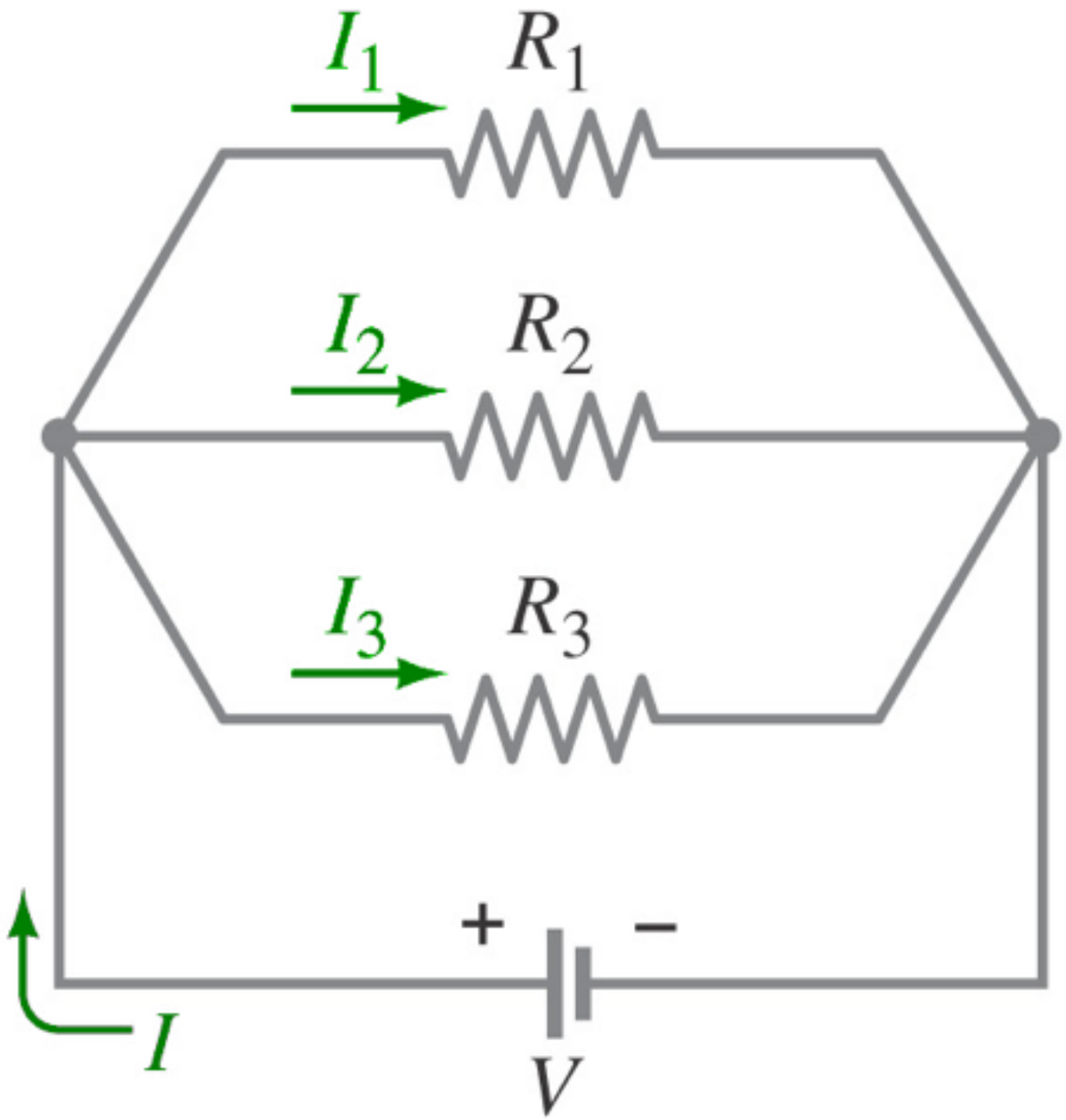
- $V = V_1 + V_2 + V_3 + V_4$
  $= IR_1 + IR_2 + IR_3 + IR_4$
- The battery doesn't know the difference between one big resistor and several small resistors working together
- $V = IR_{\text{eq}}$
- $R_{\text{eq}} = R_1 + R_2 + R_3 + R_4$

Series



SERIES & PARALLEL

- Resistors connected in ***parallel*** will split the current into separate branches
- The "forks in the road" where current can split off into multiple paths are called ***junctions***
- $I = I_1 + I_2 + I_3$



SERIES & PARALLEL

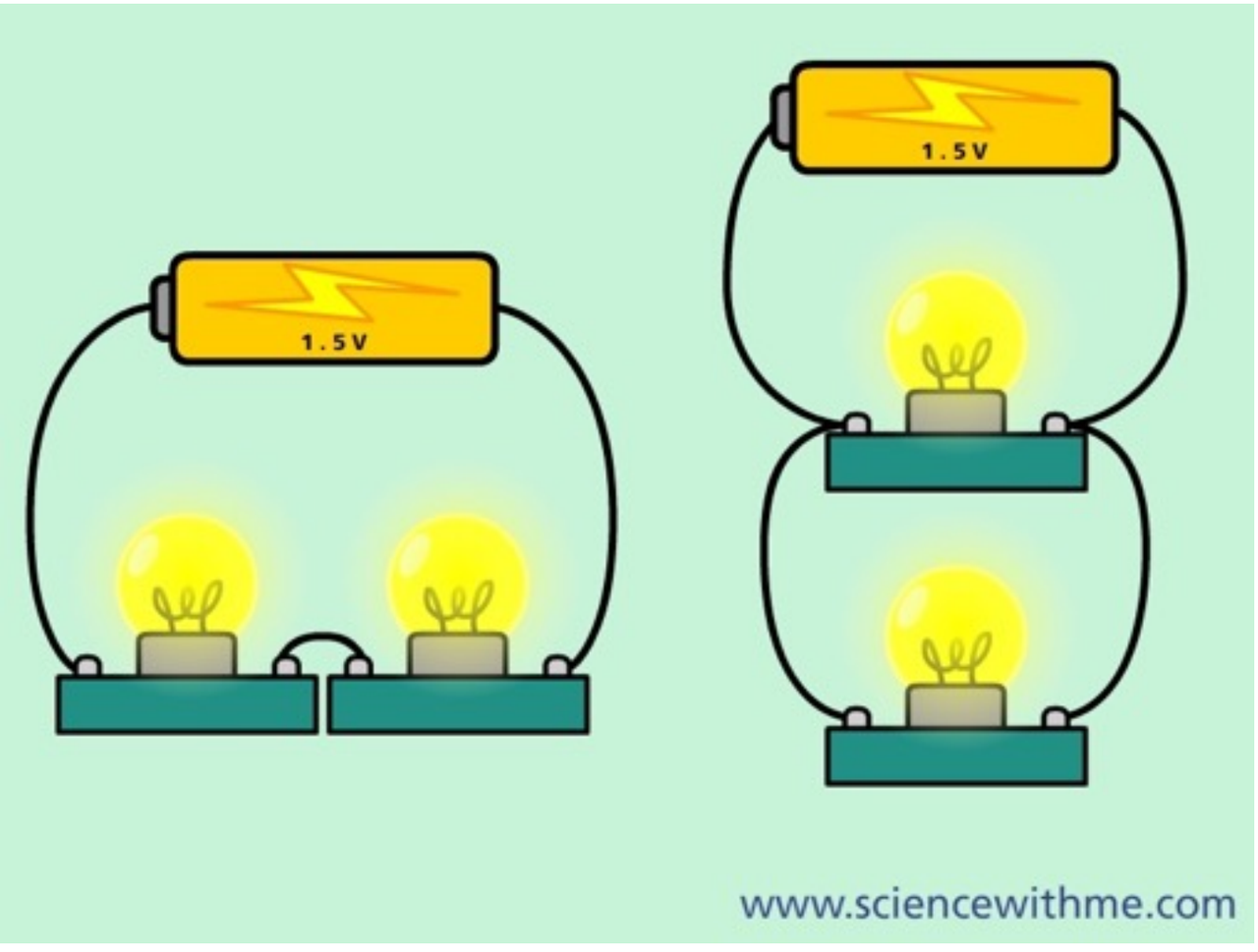
- When resistors are connected in parallel, each experiences the *same voltage*

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$$

Parallel

SERIES & PARALLEL

	Series	Parallel
V	$V = V_1 + V_2 + V_3 + \ldots$	constant
I	constant	$I = I_1 + I_2 + I_3 + \ldots$
R	$R_{eq} = R_1 + R_2 + R_3 + \ldots$	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots$



SANITY CHECK

a) The lightbulbs are identical and have identical resistance. Which configuration produces more light?

b) Which way do you think the headlights of a car are wired?

a) The parallel combo has less resistance than the series, so it will be brighter in parallel

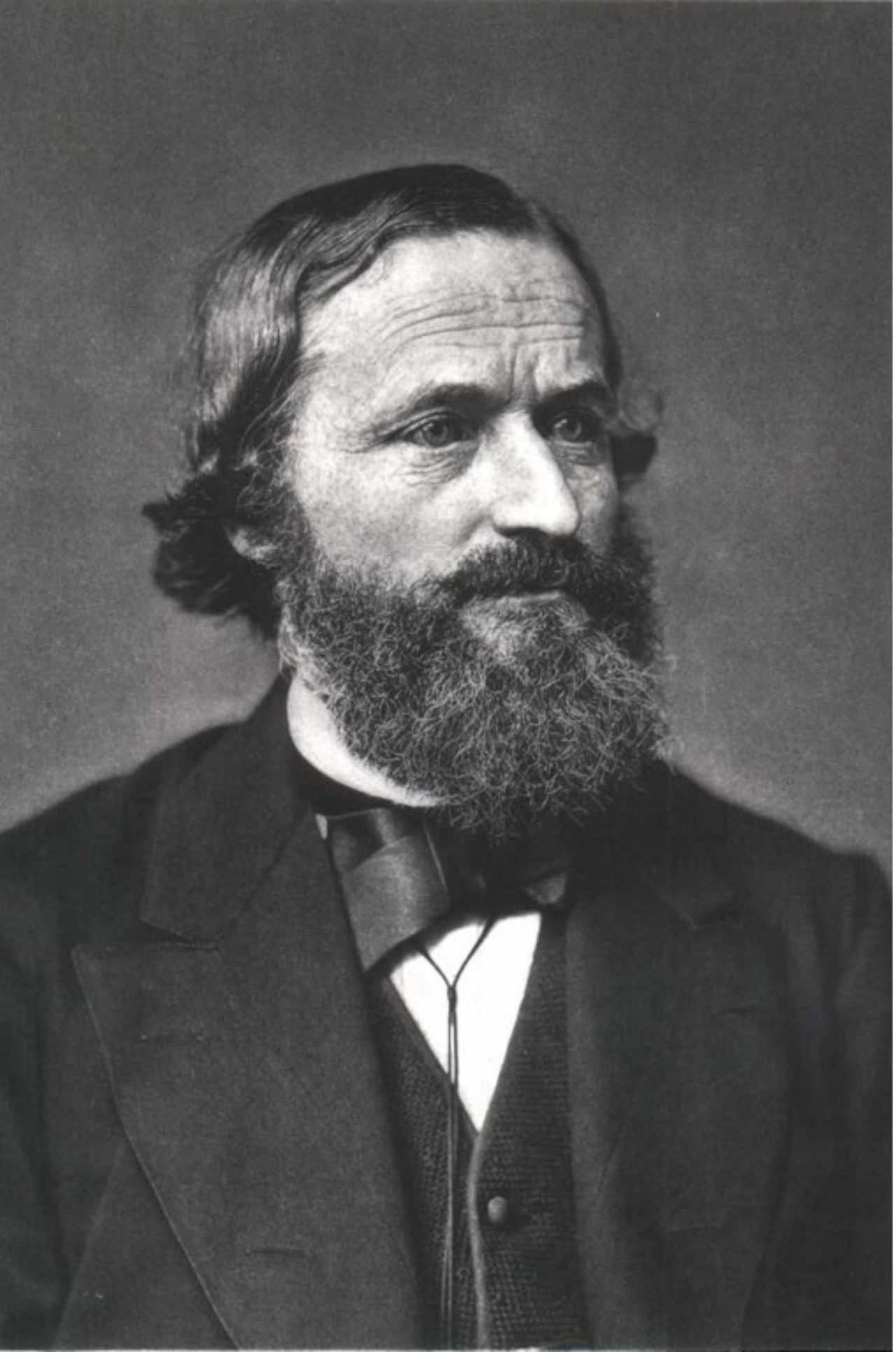
b) In parallel, because if one goes out, the other light can stay lit

EXAMPLE 6

➤ Two circuits both are built from one 24-V battery and two 100-Ω resistors. In the first circuit the resistors are connected in (*a*) series, in the second they are in (*b*) parallel. What is the current through each resistor and what is the equivalent resistance of each circuit?

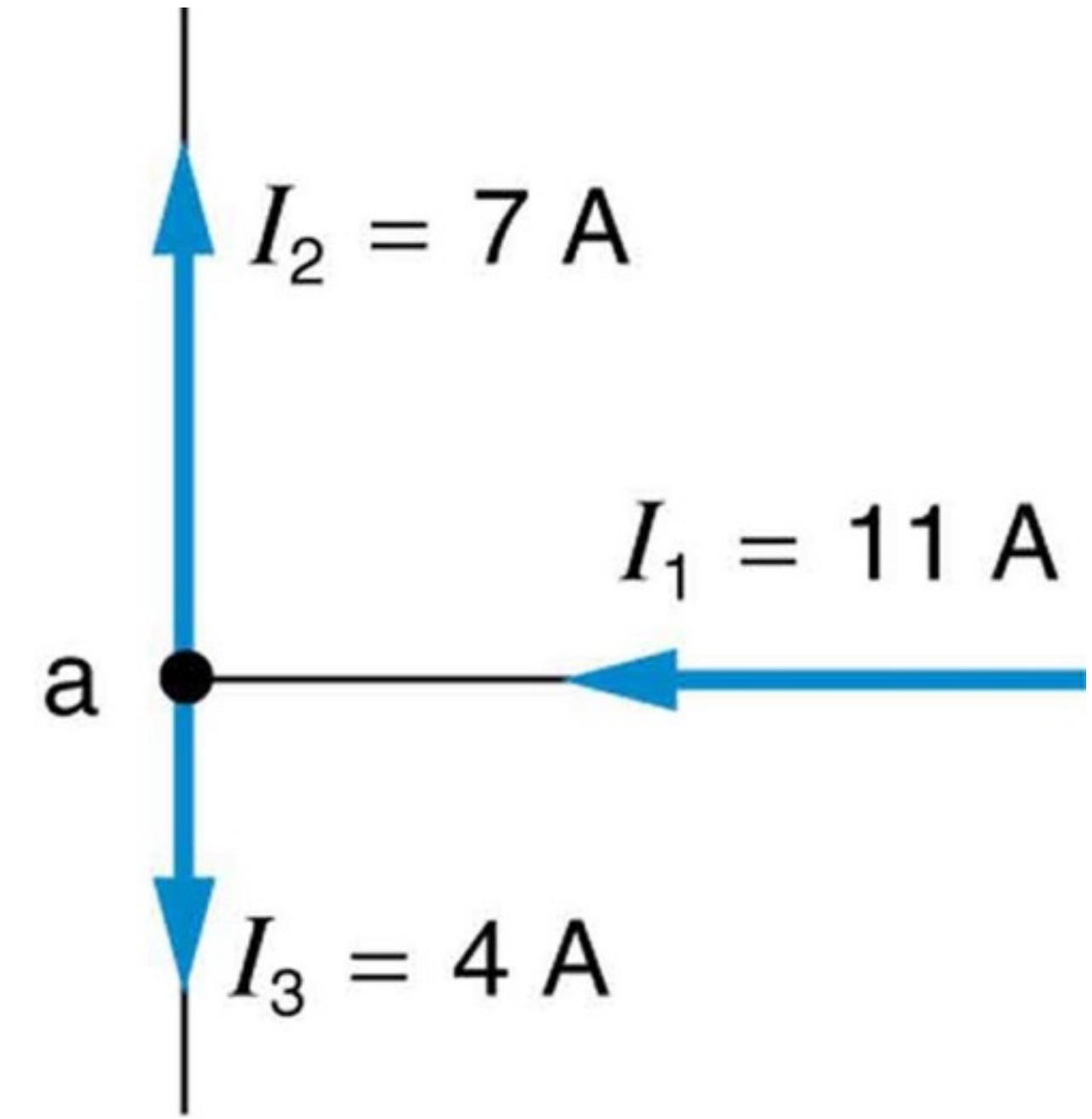
a) Ans. $I = 0.120\ A;\ R_{eq} = 200\ \Omega$

b) Ans. $I = 0.48\ A;\ R_{eq} = 50\ \Omega$



KIRCHHOFF'S RULES

- So far, we've been able to find the currents in circuits by combining resistances in series and parallel and using Ohm's Law
- Sometimes circuits are too complicated for this type analysis
- In the mid-nineteenth century, G. R. Kirchhoff invented two rules for dealing with such complicated circuits



$$I_1 = I_2 + I_3$$

KIRCHHOFF'S RULES

- The rules are really just convenient applications of conservations of charge and energy

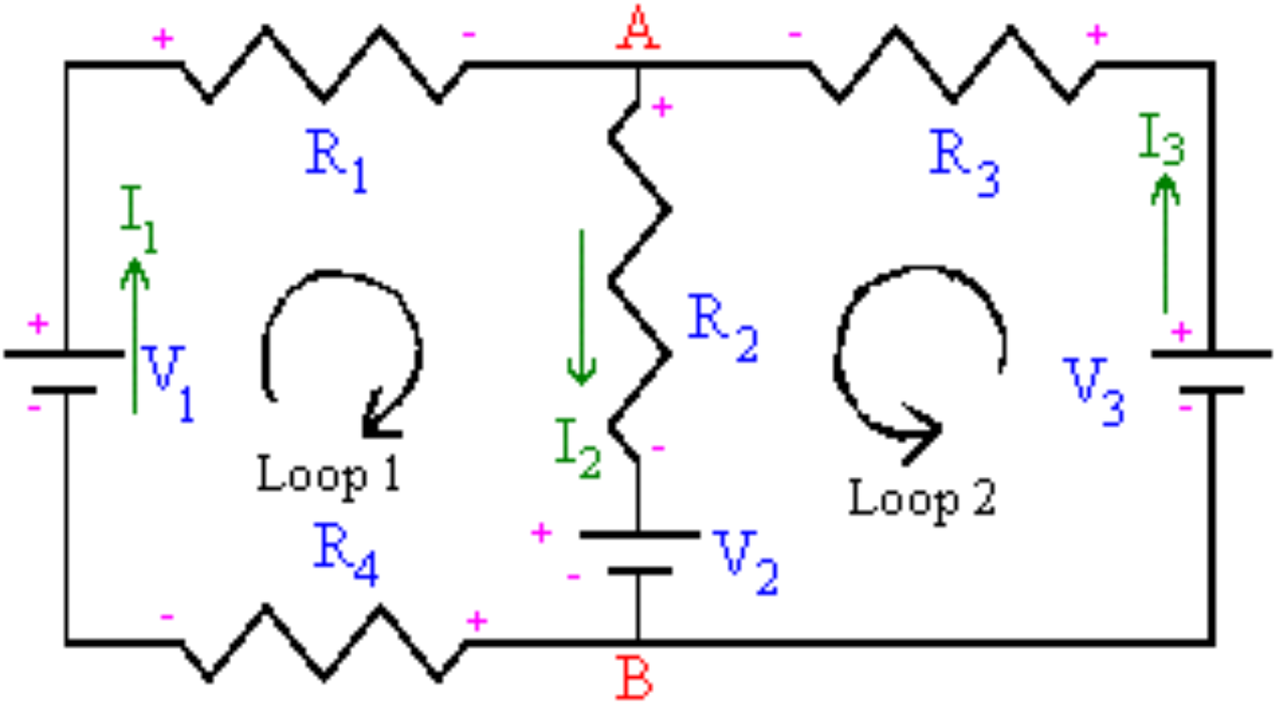
1. ***Junction Rule*:** at any junction, the sum of currents in equals the sum of currents out

- (conservation of charge)

KIRCHHOFF'S RULES

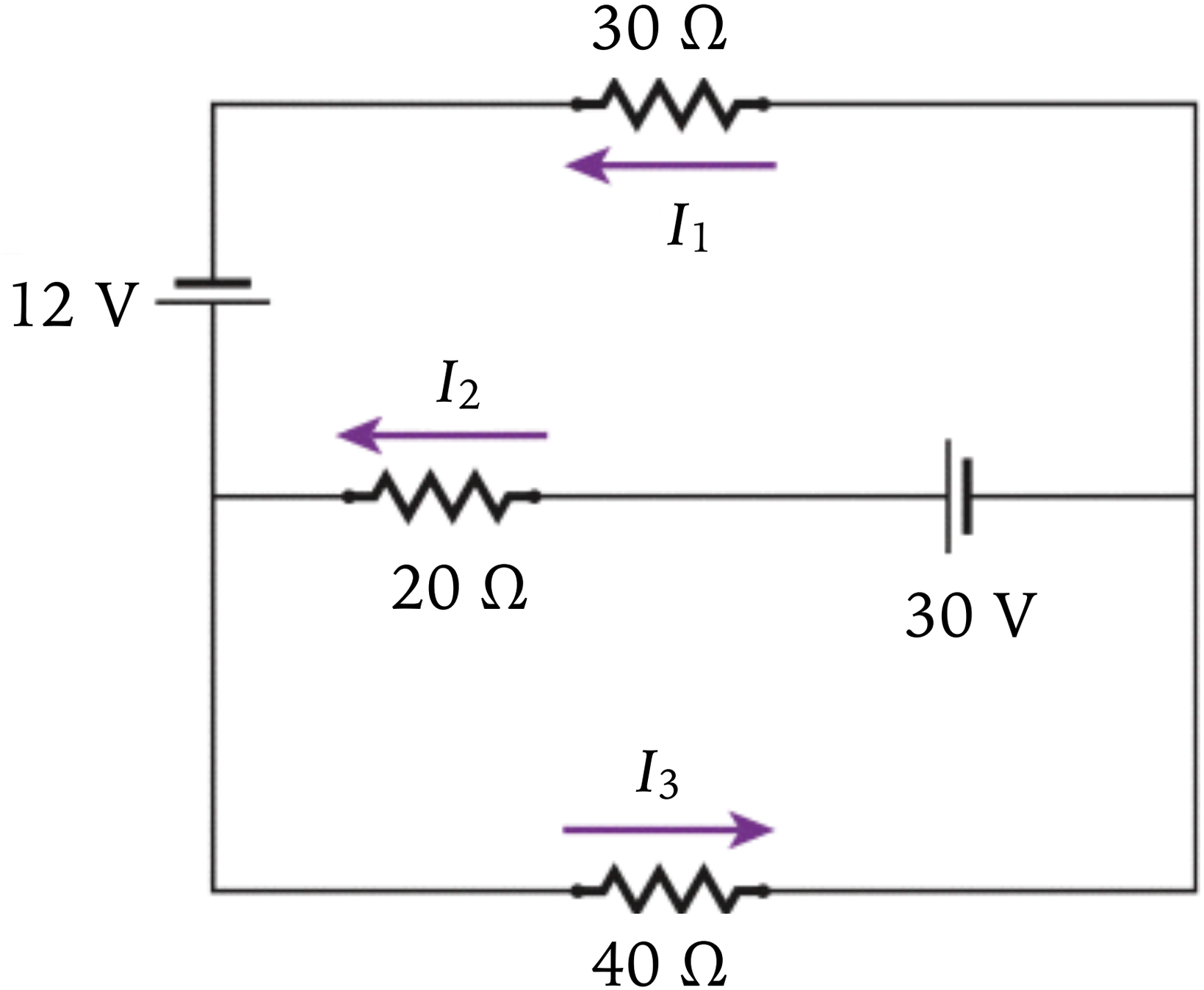
2. ***Loop Rule***: the sum of the changes in potential around any closed path of a circuit must be zero

   ➤ (conservation of energy)

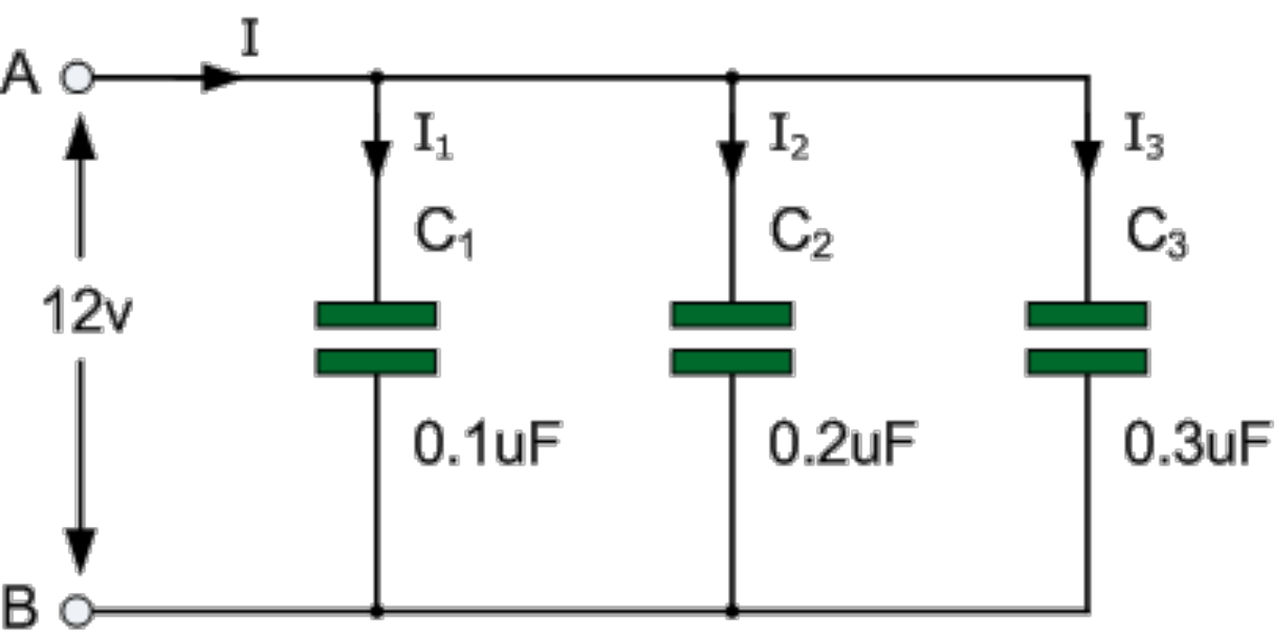


EXAMPLE 7

- Calculate the currents I_1, I_2, and I_3 in each of the branches of the circuit
- *Ans.* $I_1 = -0.19\ A$;
  $I_2 = 0.62\ A$;
  $I_3 = 0.44\ A$

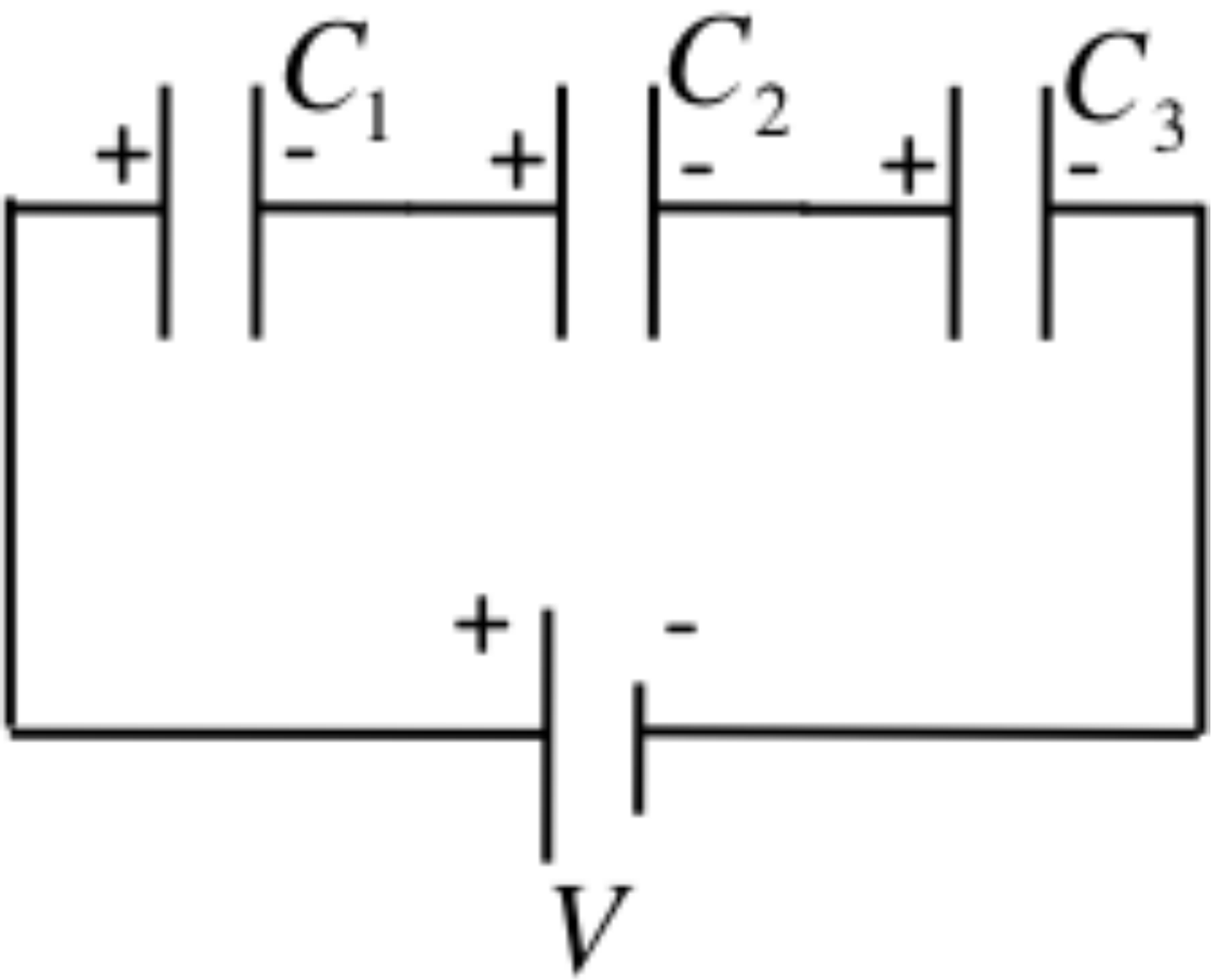


CAPACITORS IN CIRCUITS



- Capacitors in parallel:
  - The junction rule tells us that current in equals current out, and by extension, charge in equals charge out
  - $Q = Q_1 + Q_2 + Q_3$
  - Combine with $Q = CV$
  - $C_{eq} = C_1 + C_2 + C_3$

Parallel



CAPACITORS IN CIRCUITS

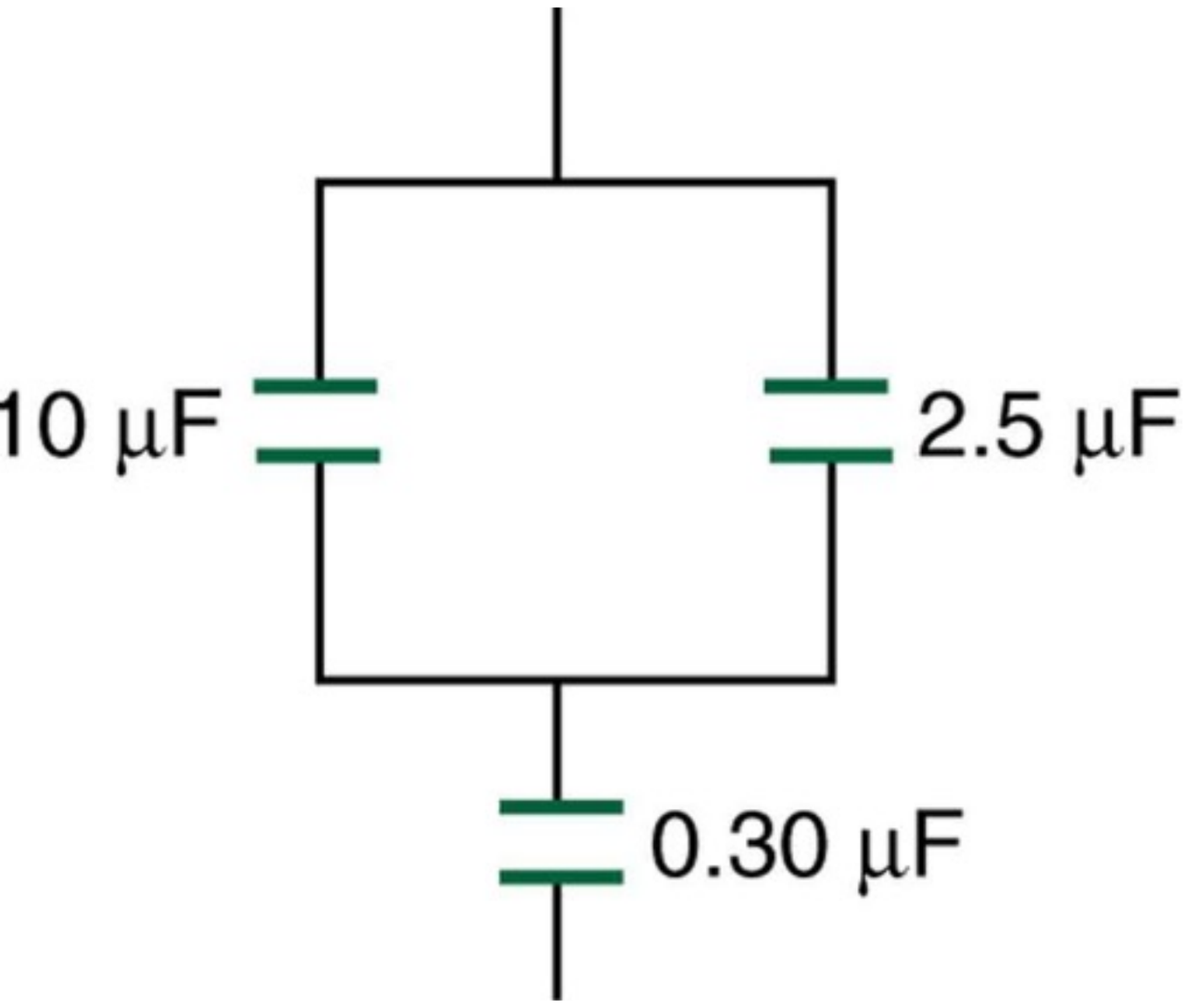
- Capacitors in series:
  - Conservation of energy tells us that electric potential supplied by the battery will equal the sum of the potentials used up by circuit components
- $V = V_1 + V_2 + V_3$
- Combine with $Q = CV$

$$\frac{1}{C_T} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3}$$

Series

EXAMPLE 8

- Determine the capacitance of a single capacitor that will have the same effect as the combination shown
  - *Ans.* $C_{eq} = 0.29\ \mu F$



LIGHTNING, PART 2

- *"Electricity is really just organized lightning" — George Carlin*
- Could you really power a city by harnessing the electrical power of lightning?

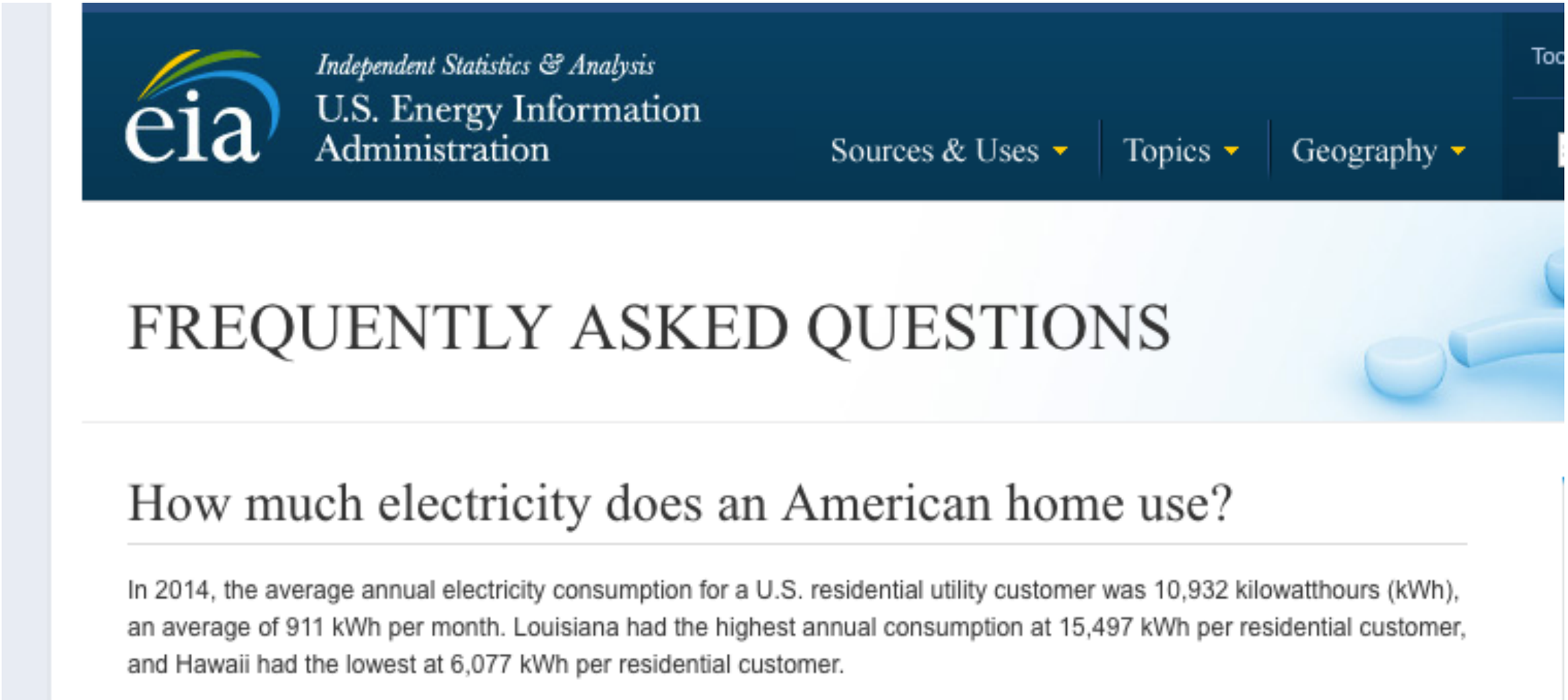
LIGHTNING, PART TWO

- The average lightning bolt can deliver roughly 10,000 A of current in the span of only 100 μs.
- The potential difference needed for lightning to strike is dependent on the breakdown voltage of air. Given the average distances between the storm cloud and ground, it would require around 150 MV for lightning to strike.
- How many joules of energy are contained in a bolt of lightning?
  - *Ans. $E = 150$ million joules*

https://goo.gl/d8iFrR

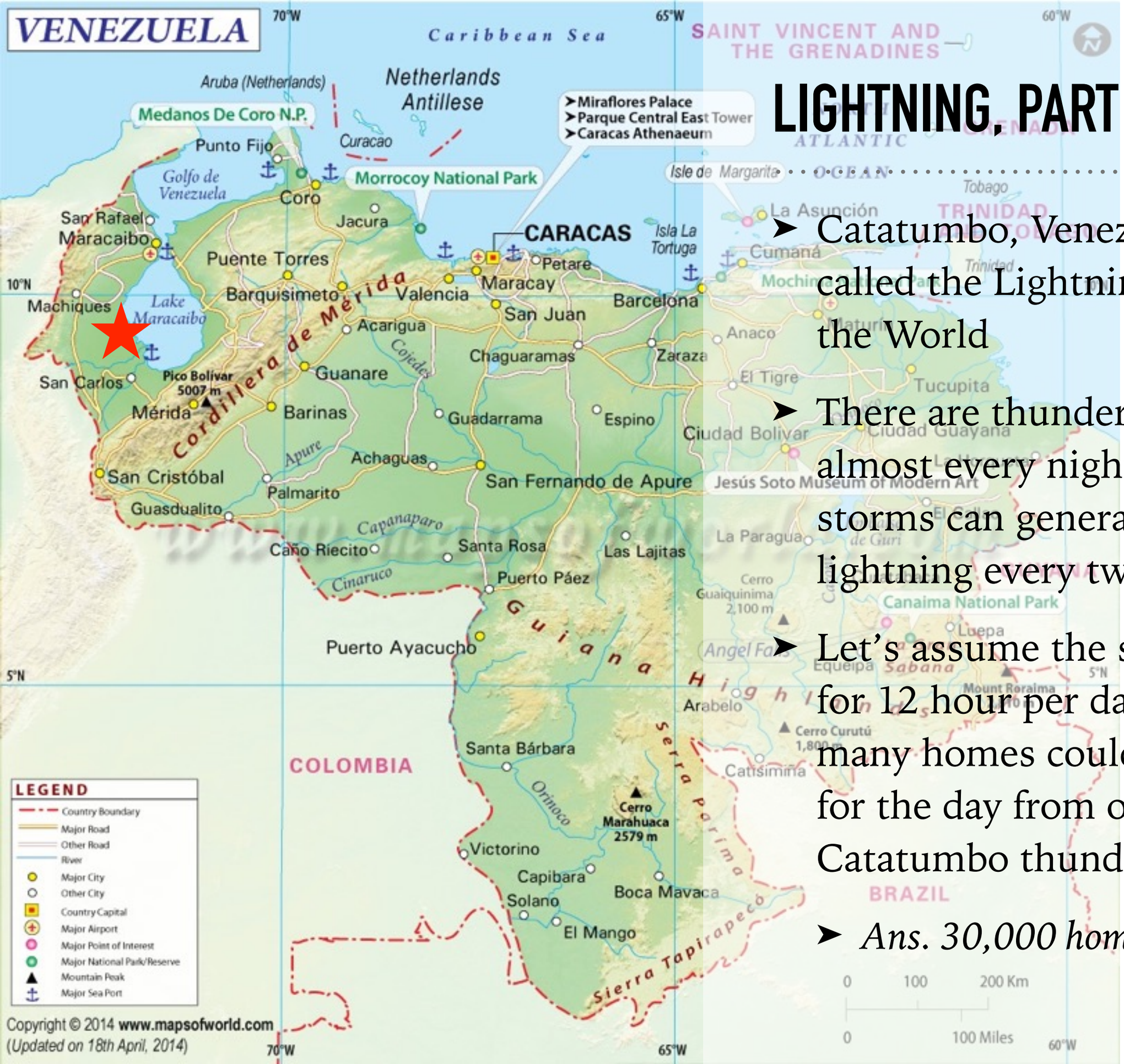
LIGHTNING, PART II

- According to eia.gov, how many joules of energy does the average American household use per day?
  - *Ans.* $P_{avg} = 1.08 \times 10^8\ J/day$



LIGHTNING, PART TOO

- For how many days could a single bolt of lightning power a home?
- *Ans. 1.4 days*

LIGHTNING, PART DOS

- Catatumbo, Venezuela is called the Lightning Capital of the World
- There are thunderstorms almost every night, and these storms can generate a flash of lightning every two seconds.
- Let's assume the storms last for 12 hour per day. How many homes could you power for the day from one night of Catatumbo thunderstorms?
- *Ans. 30,000 homes*