Chapter 06

Electricity

Section 6.1

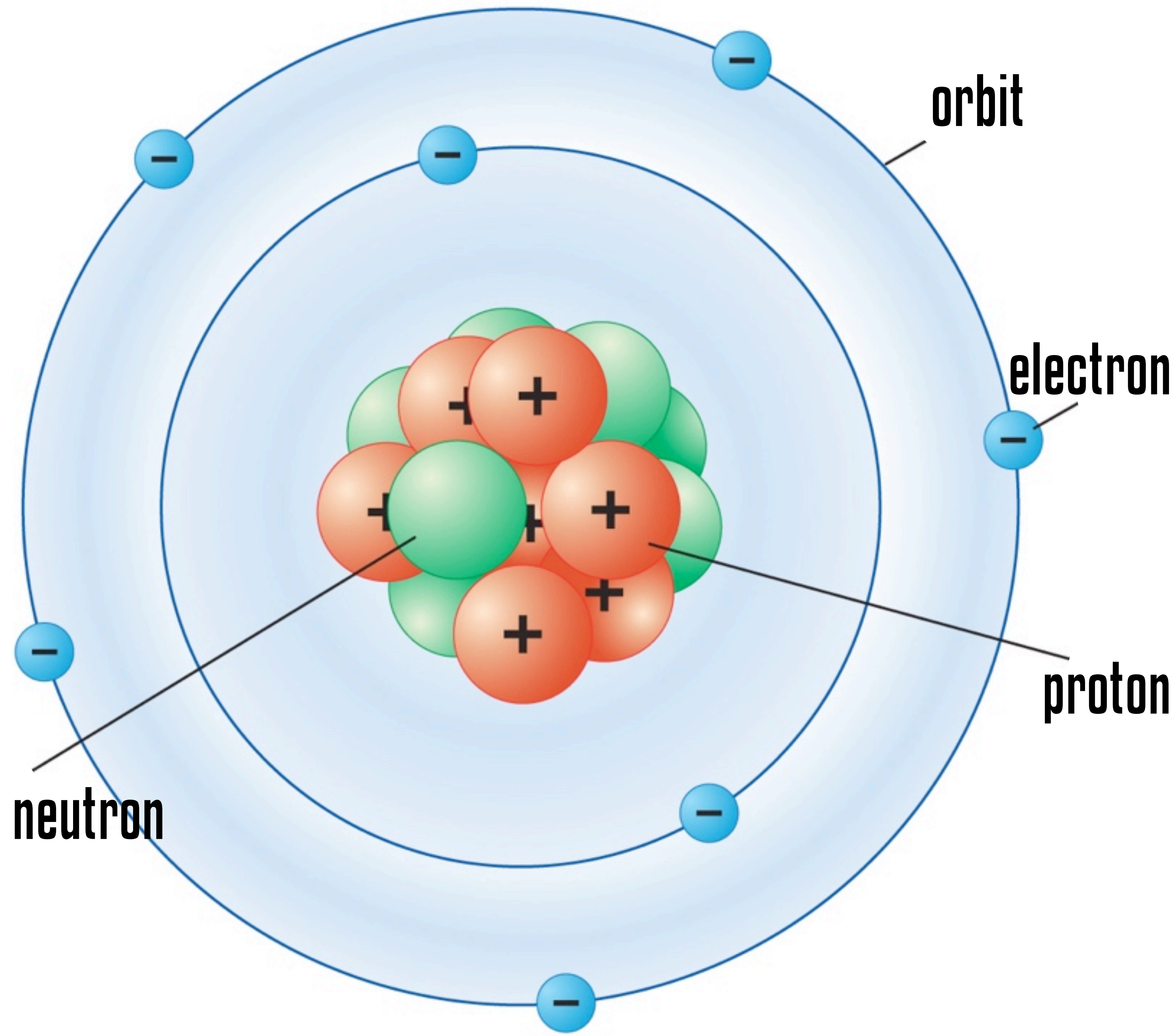
Concepts of Electricity

Electron Theory of Charge

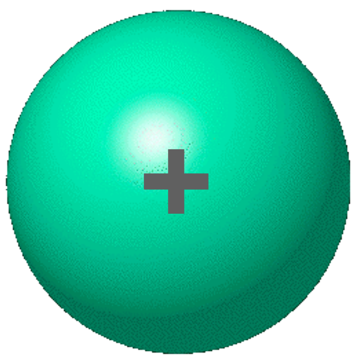
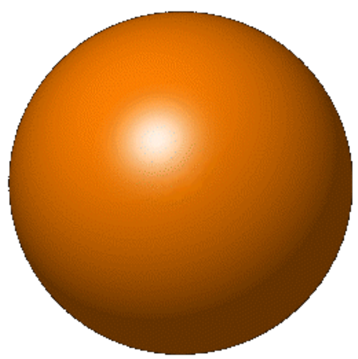
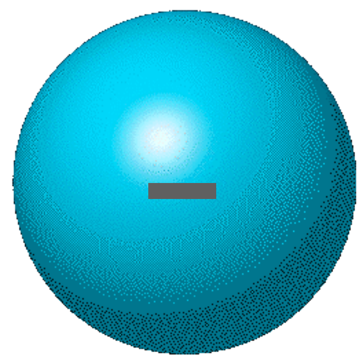
- Amber Effect: Known since at least the time of the ancient Greeks, rubbing a piece of amber with a cloth would allow the amber to move around bits of paper, strands of hair
- Electron: From the Greek word for amber; these were not discovered until 1897!
- Electricity: Same Greek root, but you are not rubbing bits of amber to power up your laptop

Atoms

- Nucleus containing protons and neutrons
- Electrons in orbit around nucleus
- We are mostly concerned wit these electrons, and how/why they move

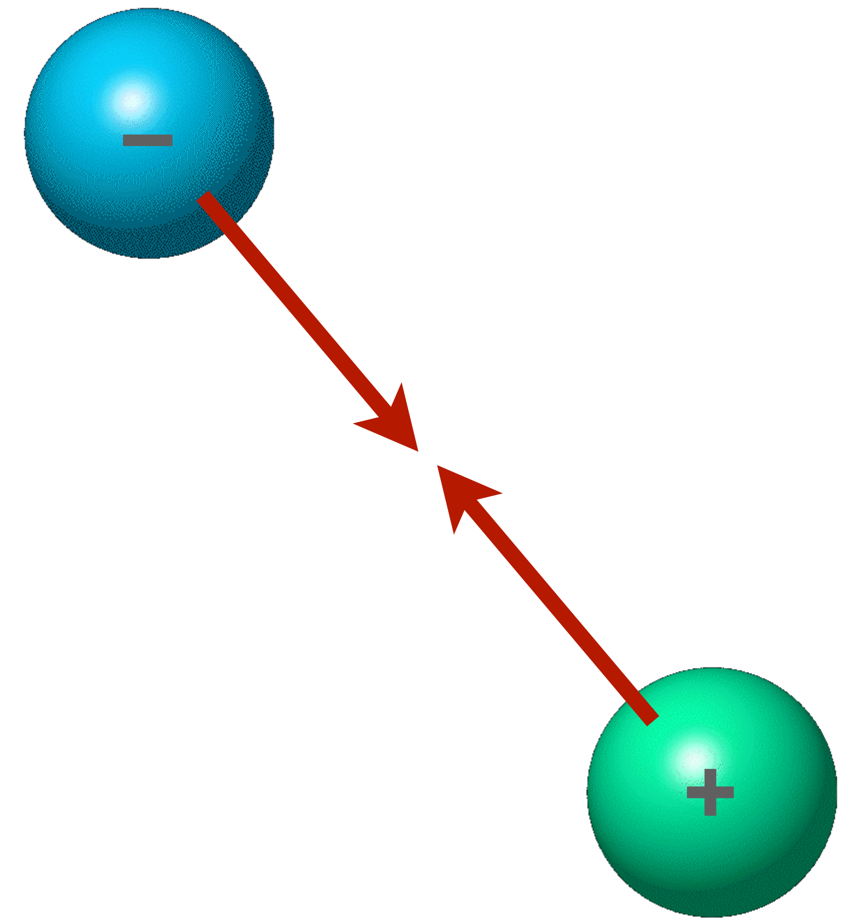


Electric Charge

		
proton	neutron	electron
Charge (Coulombs)		
$+1.6 \times 10^{-19}$	0	-1.6×10^{-19}
Mass (kg)		
1.67×10^{-27}	1.67×10^{-27}	9.1×10^{-31}

- Charge is a fundamental material property: All matter is made of atoms that are made of particles that carry charge
- Charge is a lot like like mass; you know it when you see it (or feel it...), but it defies easy description
- Two types of charge: negative (electrons) and positive (protons)

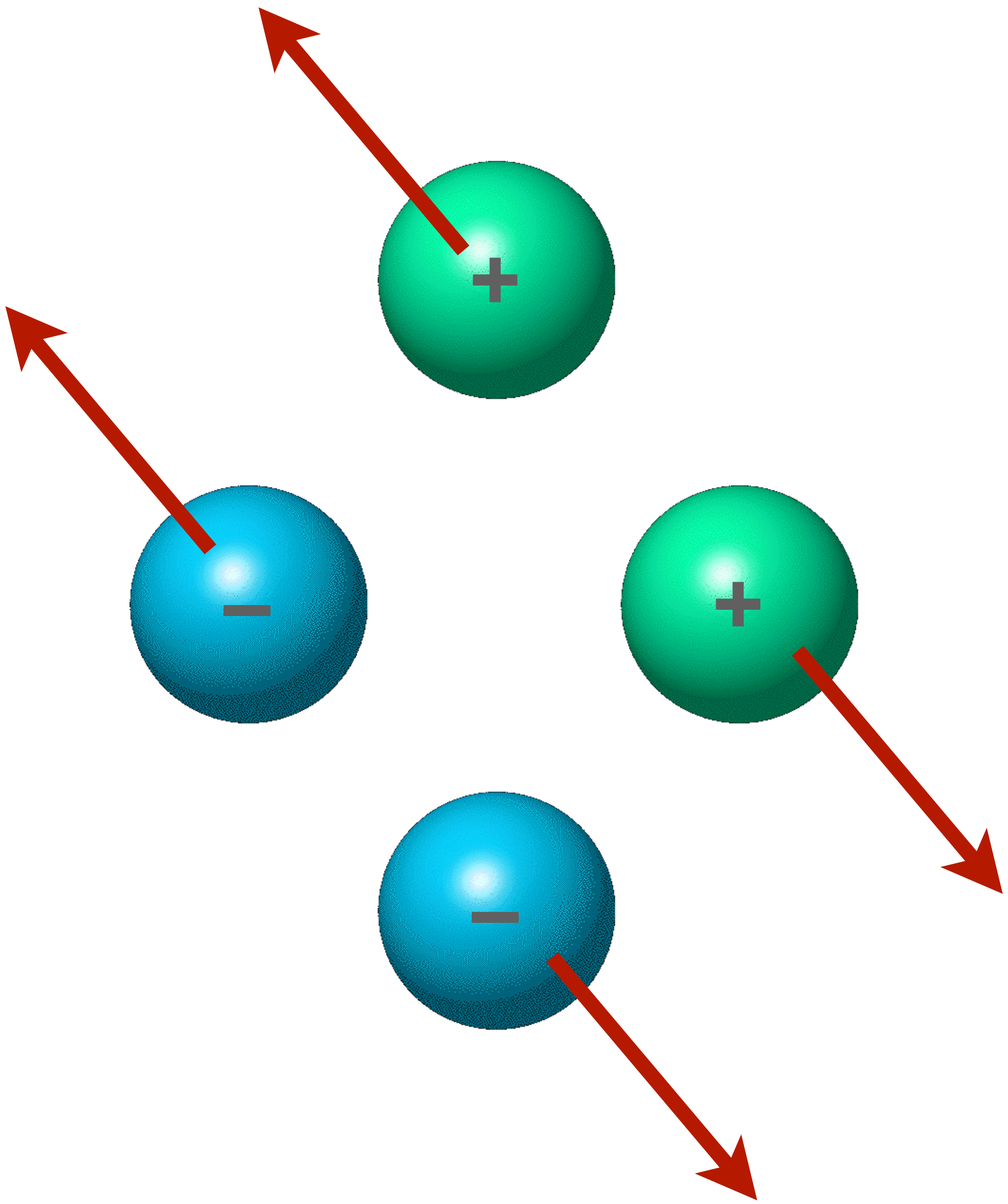
Mutual Attraction



- Opposite charges attract each other
- Negative attracts positive

True or False: A proton will be electrically attracted to a neutron.

Mutual Repulsion

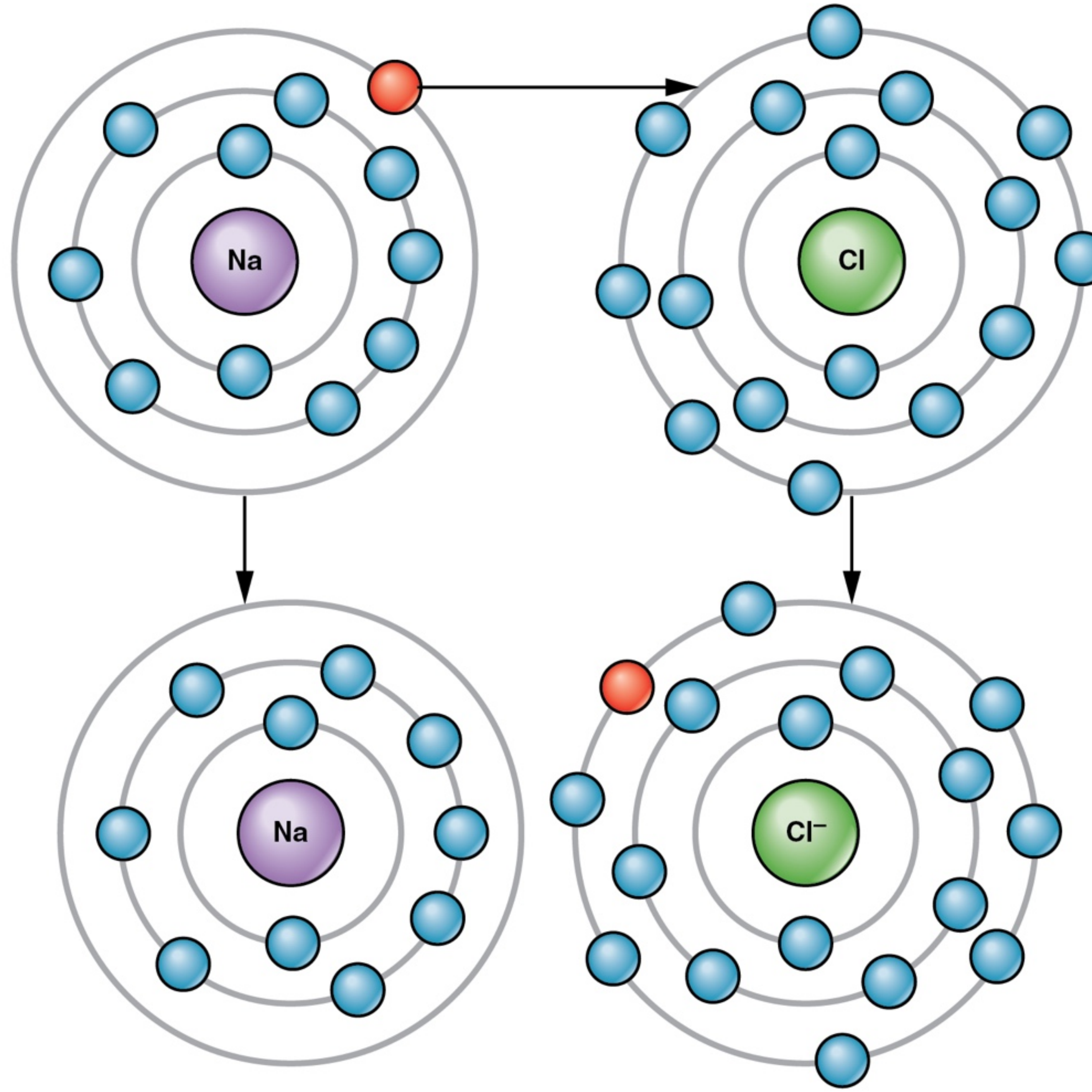


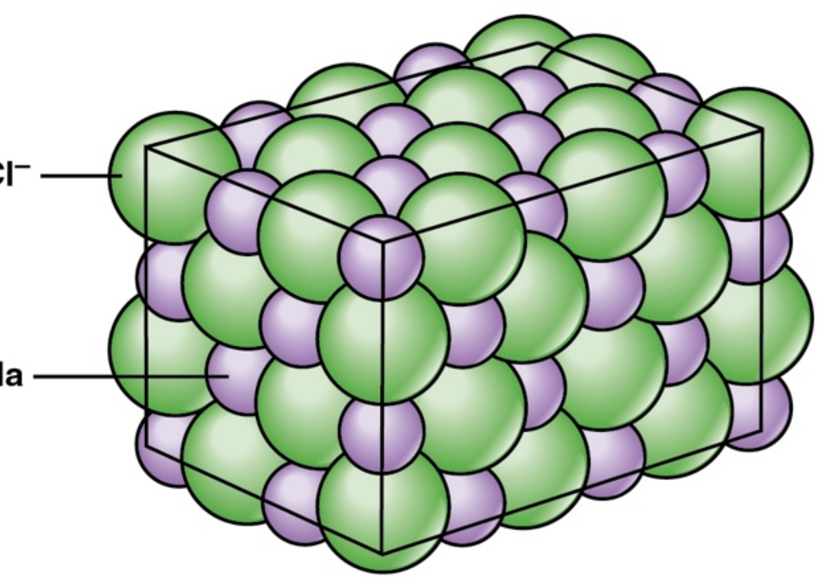
- Like charges repel each other
- Negative repels negative
- Positive repels positive

True or False: A proton will be electrically repelled by an electron.

Ions

- Most atoms are electrically neutral: Same number or (+) and (–) charges
- Ion: Add or subtract an electron (Only an electron! You are not pulling protons out of the nucleus!)
- Positive Ion: Remove one or more electrons
- Negative Ion: Add one more electrons



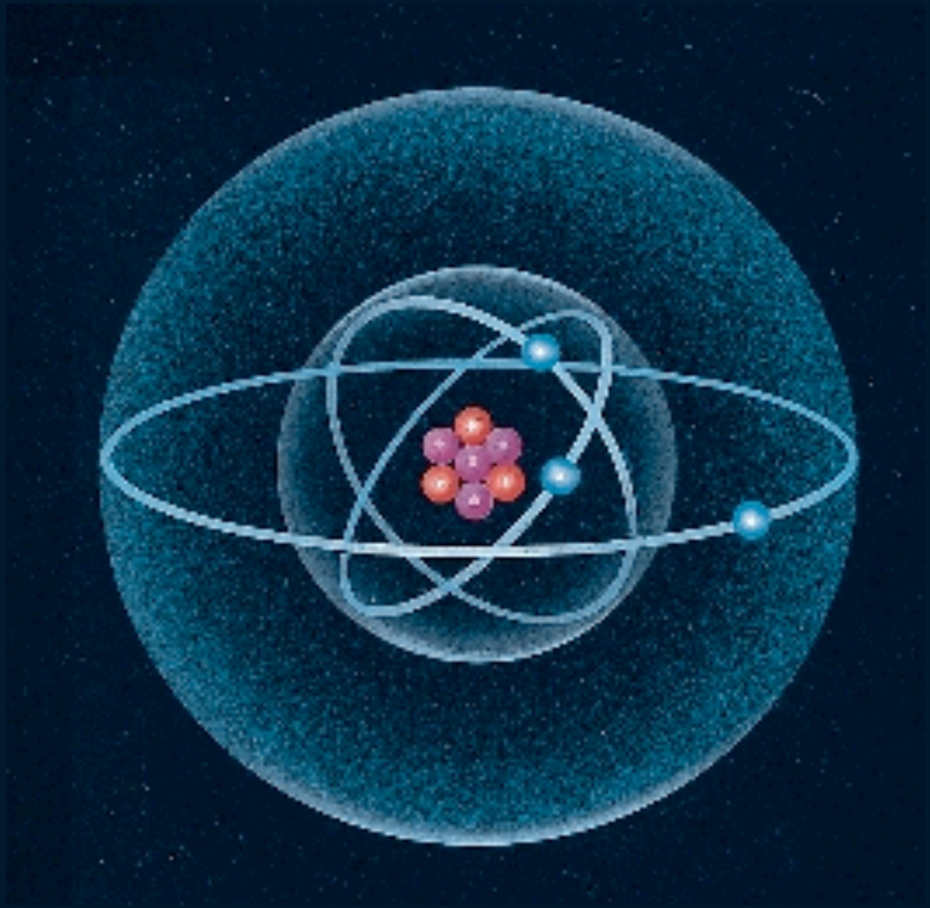


The lithium ion shown is

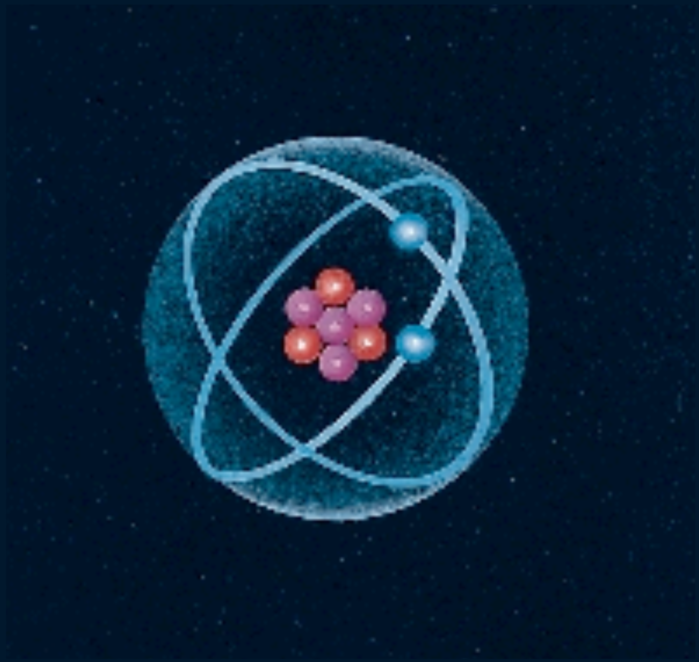
A) positively charged.

B) negatively charged.

C) neutral.



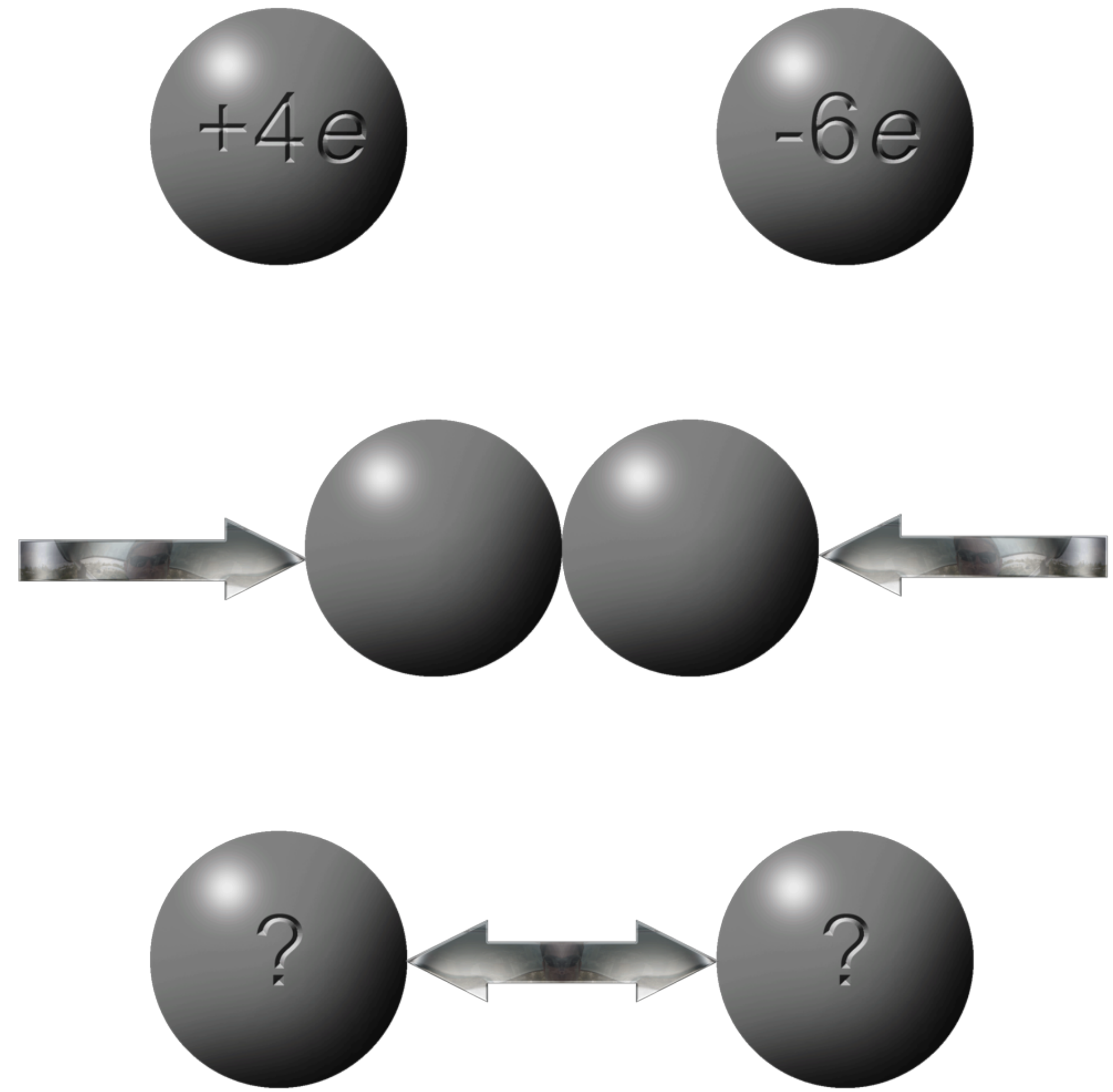
LITHIUM ATOM



LITHIUM ION

You Can Move It, But You Can't Lose It

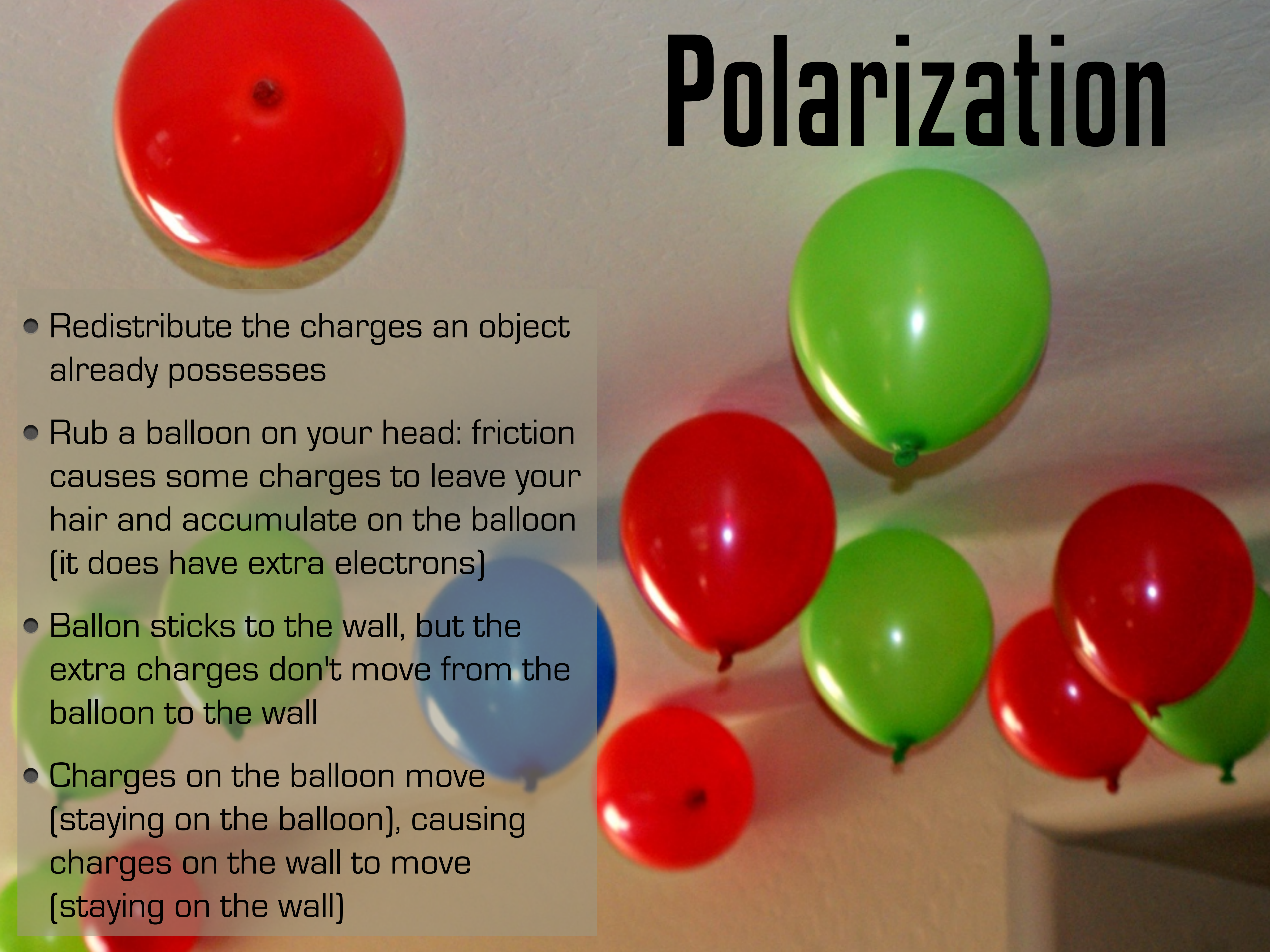
- Possible (and relatively easy) to move charges around
- New charges cannot be created out of nothing
- Existing charges cannot be destroyed
- Moving charge means they go from somewhere to somewhere–they can't just appear or disappear into or out of nowhere
- Conservation of Charge is the direct result of Conservation of Matter!



Q06.04: What is the charge on each sphere after they touch? Answer numerically!

Static Electricity

- Electrostatic Charge: Excess charge is stuck on an object (not flowing like a current)
- Scuffle across the carpet in your socks: You have used friction to scrape some electrons off the carpet, and onto your socks
- Touch the light switch: Ouch! That shock is the result of the extra charge you accumulated transferring to the metal switch plate

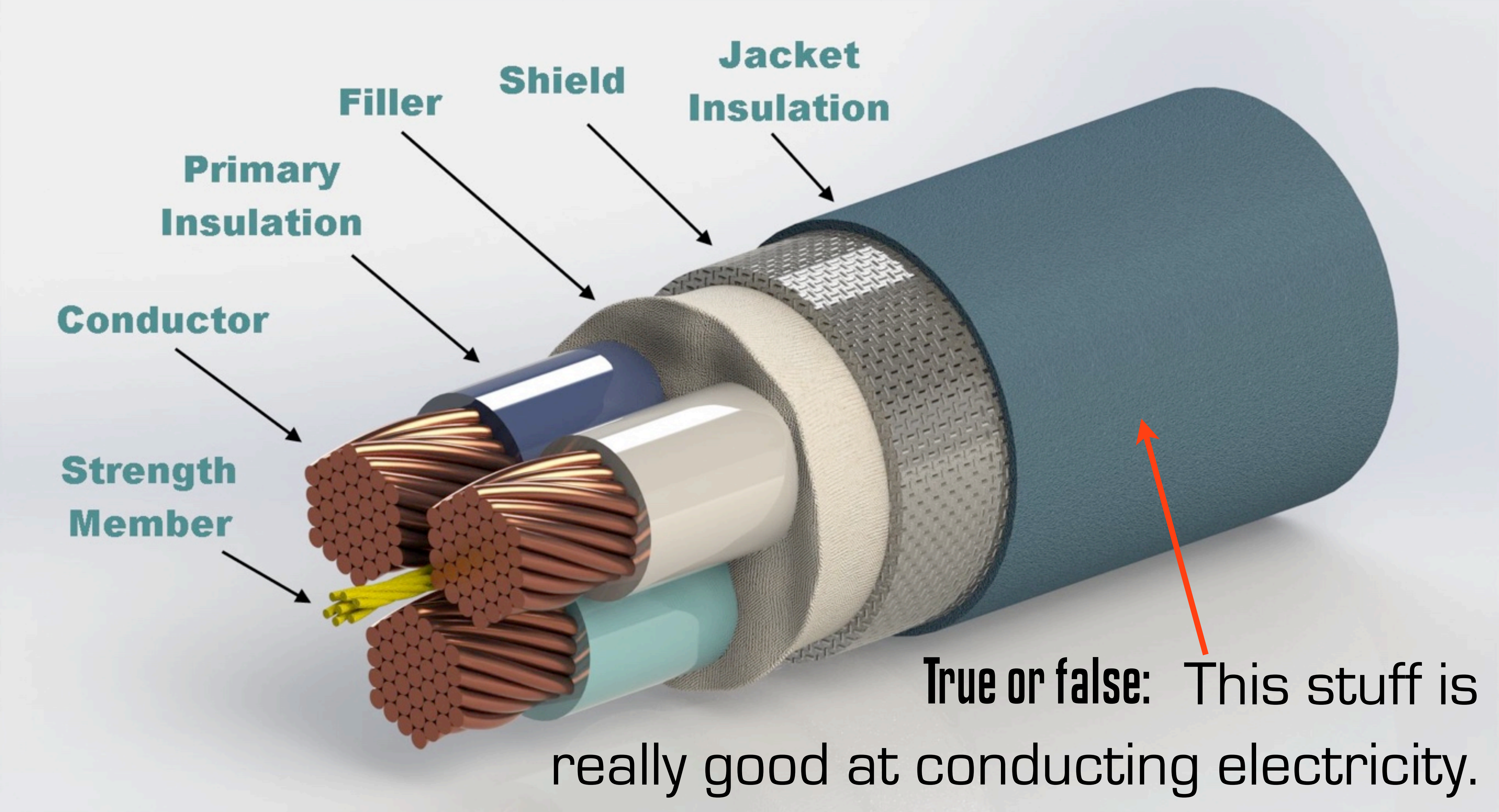


Polarization

- Redistribute the charges an object already possesses
- Rub a balloon on your head: friction causes some charges to leave your hair and accumulate on the balloon (it does have extra electrons)
- Ballon sticks to the wall, but the extra charges don't move from the balloon to the wall
- Charges on the balloon move (staying on the balloon), causing charges on the wall to move (staying on the wall)

Electrical Conductors and Insulators

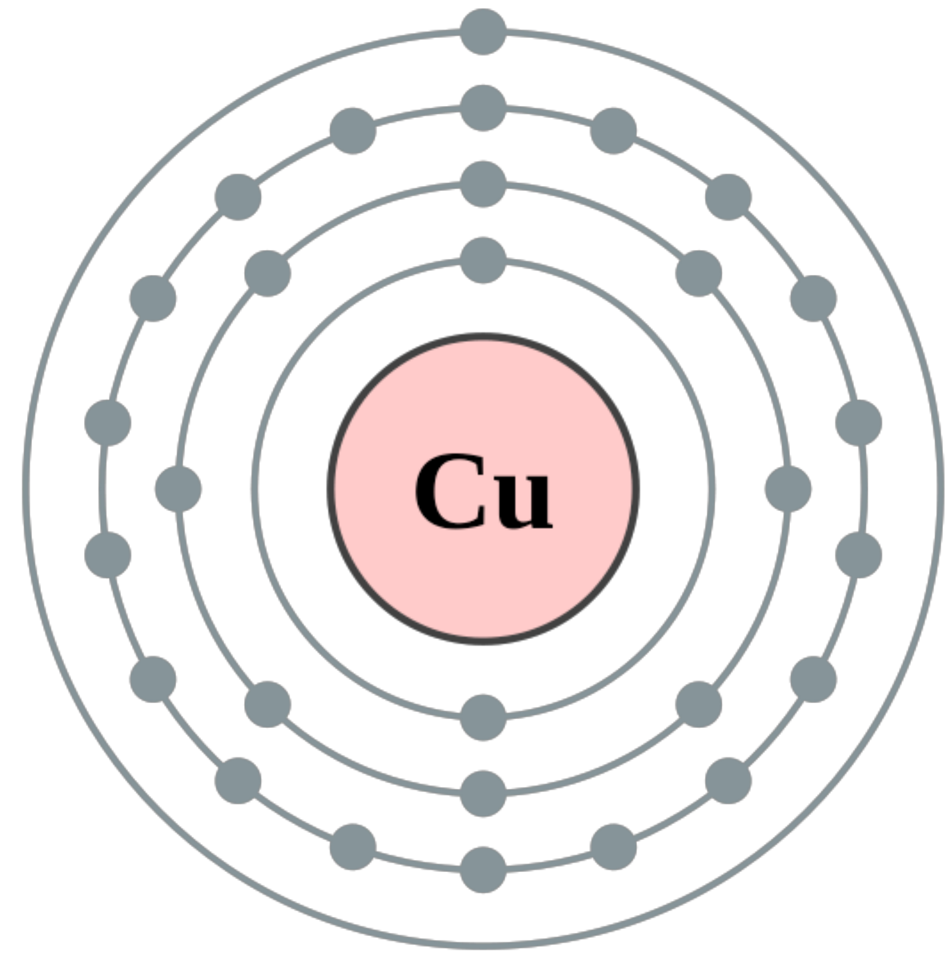
- Surprise! Not everything is equally good at moving electrons from atom to atom
- Conductors allow electrons to move easily
- Insulators prevent electrons from moving easily



True or false: This stuff is really good at conducting electricity.

Metals Are Good Conductors

- Surprise! Not really, right?
- Metals have unfilled valence shells: Outermost electron shell has room to accept extra electrons
- Crystal structure: Once you pull an e– off one atom, it's easy to transfer (the next atom over in any direction is predictable)



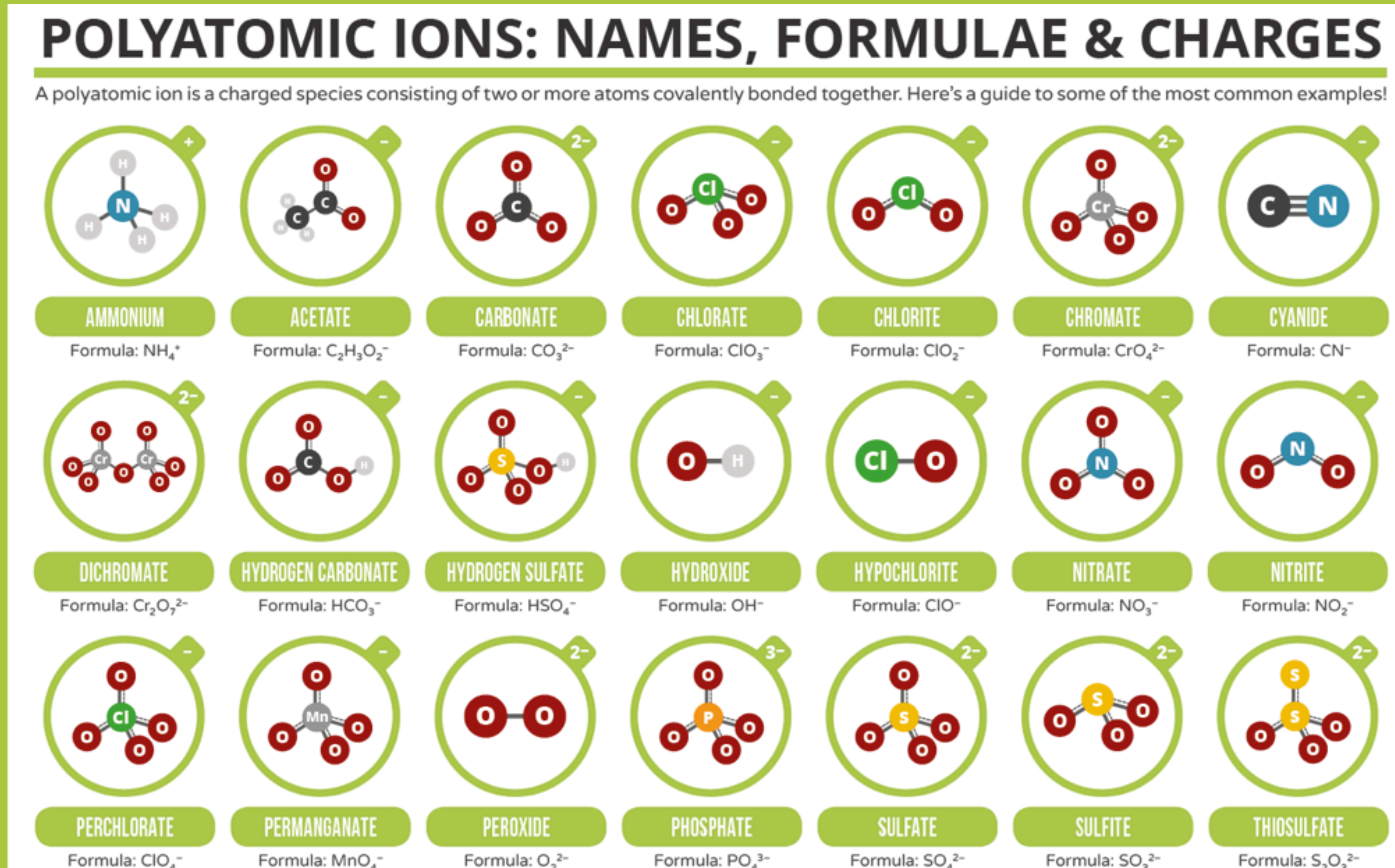
COPPER: 29 PROTONS, 29 ELECTRONS, 17 EMPTY SPACES IN THE OUTERMOST ELECTRON SHELL

Insulators

- A material that does not easily permit the motion of charges is an insulator
- Valence electrons are tightly bound, shells are full: hard to pull an e^- off, no place to put it when it gets to the next atom
- Amorphous non-metals are typically good insulators: glass, plastic, rubber, styrofoam

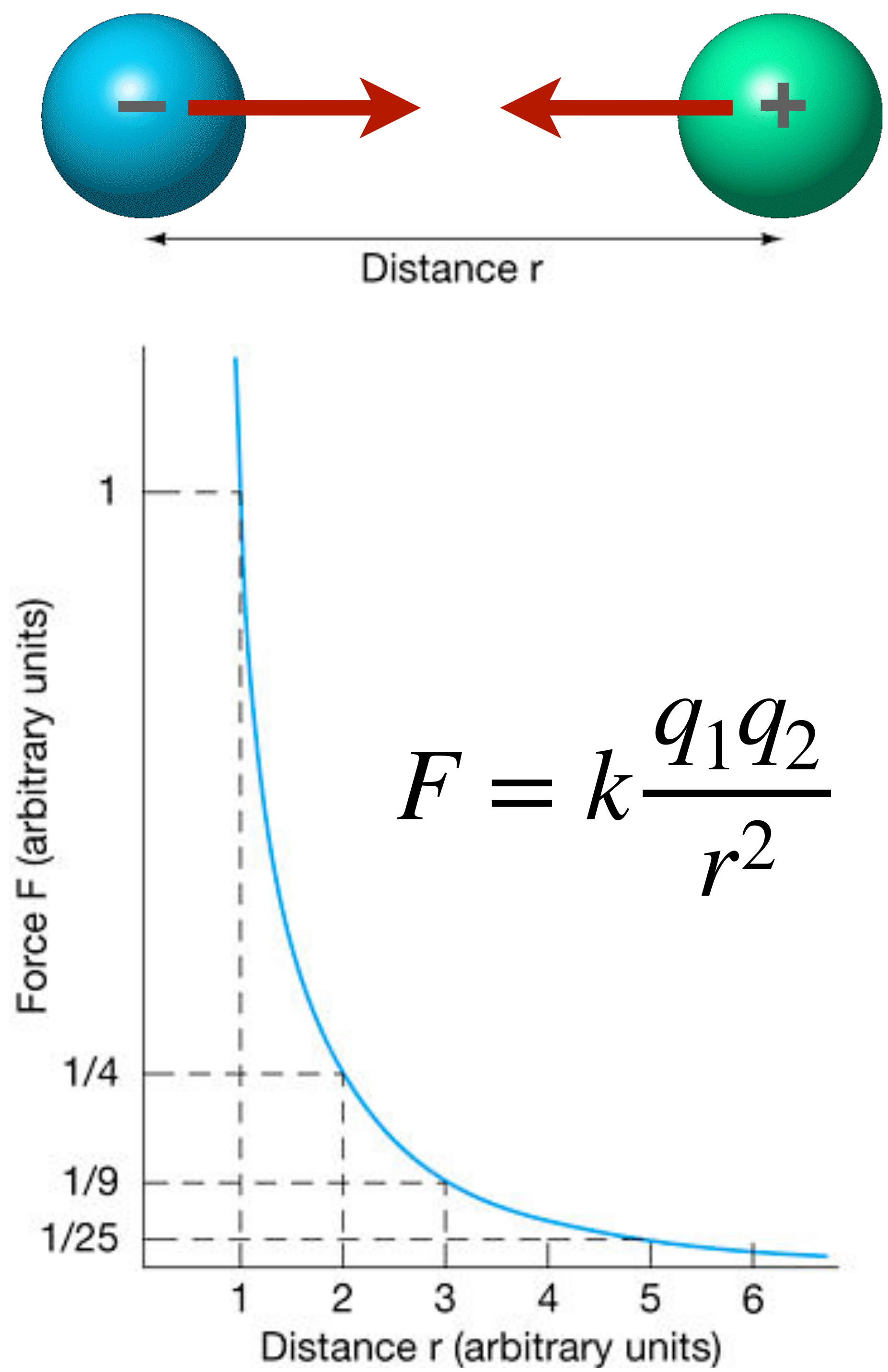
Measuring Electrical Charges

- The unit of charge is the Coulomb (C)
- Charge is quantized: Charge is carried in discrete amounts by discrete particles
- You can only have a whole number of e^- or p^+; you cannot have half an e^-
- $q = ne$: Charge on an object having n extra electrons



True or false: An ion might carry a charge of -2.4×10^{-19} C.

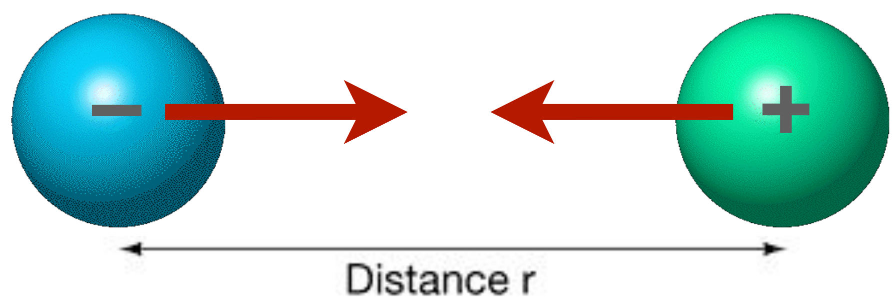
Electrostatic Force

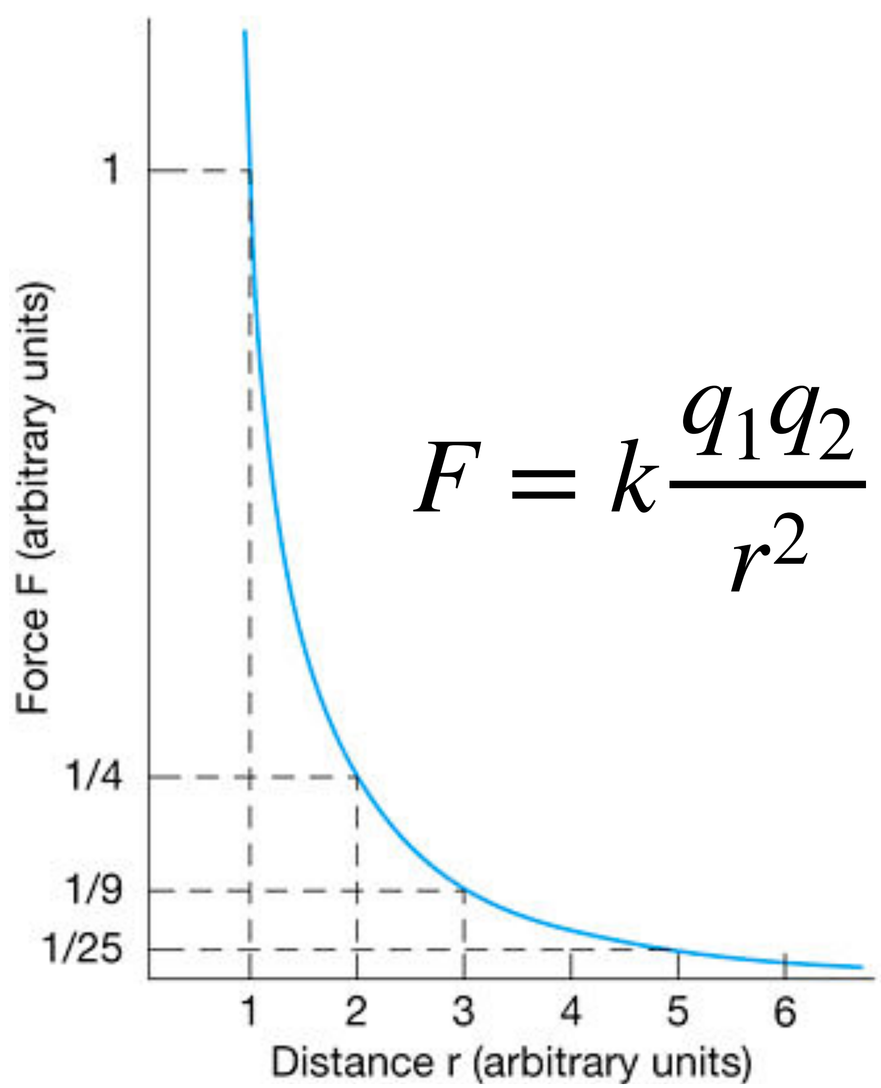


$$F = k\frac{q_1 q_2}{r^2}$$

- $k = 9\times10^9\ \mathrm{N{\cdot}m^2/C^2}$
- q_1, q_2: Charges in Coulombs
- r: Charge separation in meters
- For point charges only; charge distributions require you to integrate
- Inverse-square law: Force falls off rapidly with increased distance

The force between the charges is 16N. At half the distance, the new force will be





$$F = k\frac{q_1 q_2}{r^2}$$

A) 8 N

B) 16 N

C) 32 N

D) 64 N

E) 128 N

What is the direction of the force on charge q_1 due to charge q_2?

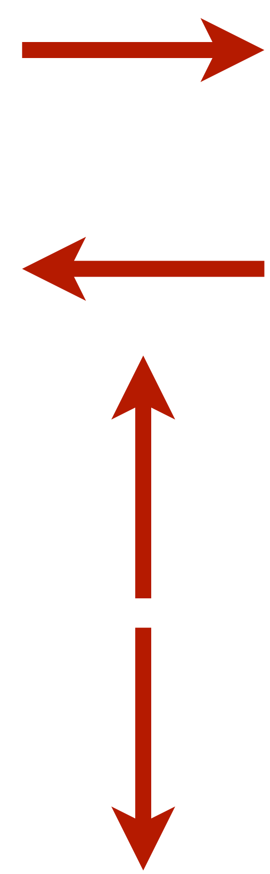
A) To the right

B) To the left

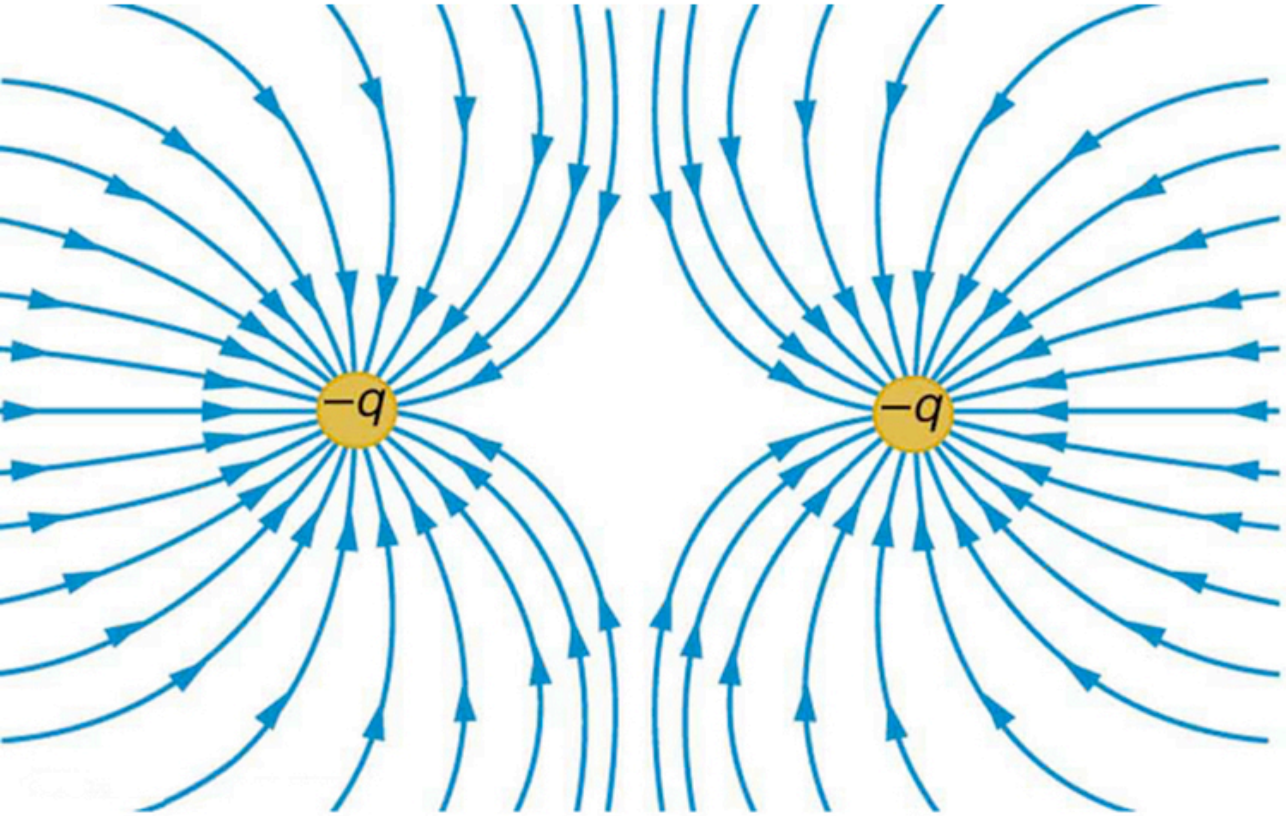
C) Up

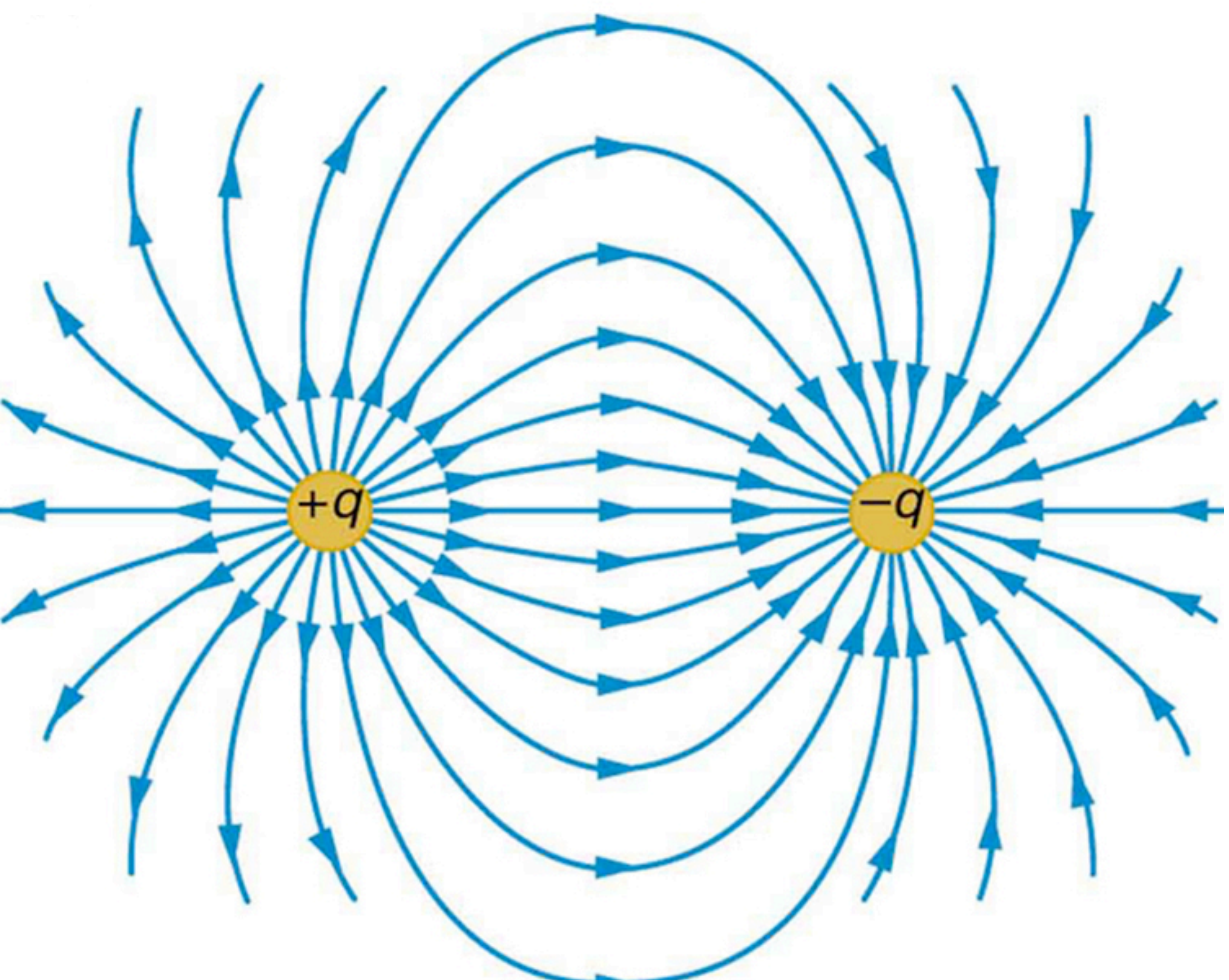
D) Down

E) Straight out of the screen



- Action at a distance: force still acts even when the objects are not in contact (gravitational, electrical, magnetic)
- "Sphere of influence"–an object that enters this sphere will be subject to a force that depends on the strength of the field created by the original object
- A field is a description (mathematical/graphical/visual) of what will happen to a test object that is subjected to that force

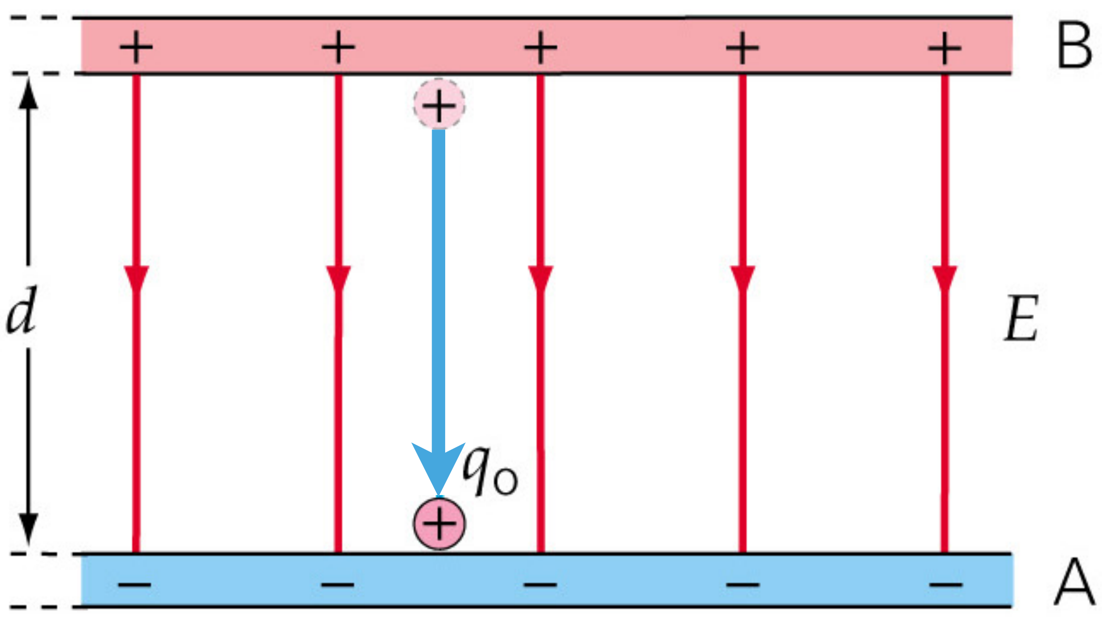


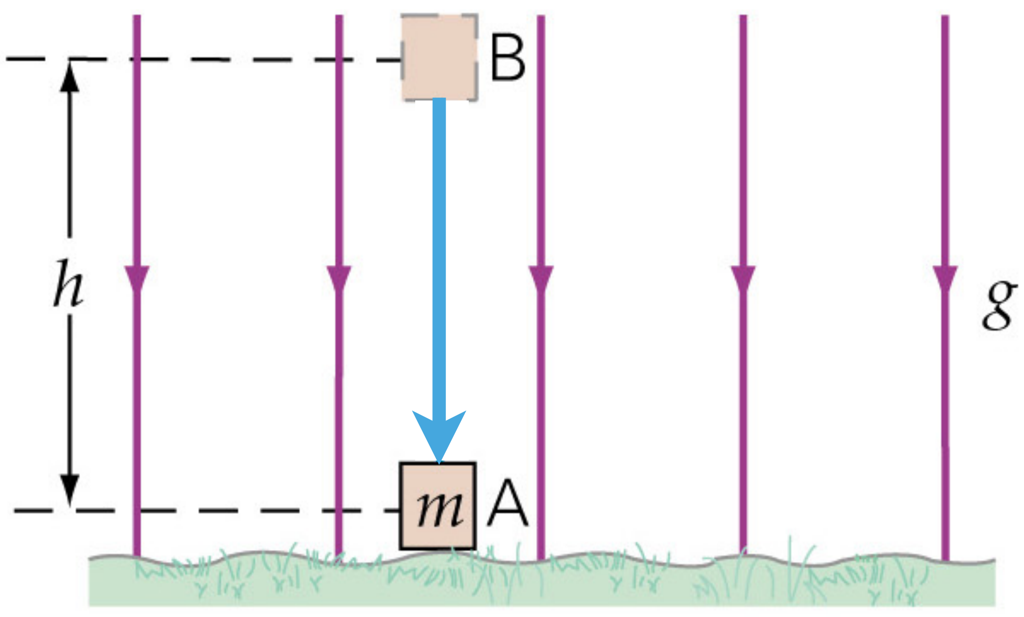


Electric Fields

- The more charge an object has, the greater its ability to exert force–the greater its field strength
- The farther away you are from this object, the less force it exerts–field strength diminishes with distance
- According to the inverse-square form of the force, the force does not go to zero until the distance reaches infinity
  This means that the sphere of influence is also infinite; field strength drops to zero at infinity
- Direction always defined by what happens to a (+) test charge

Electrical Potential





- Compare to gravity: objects with mass fall because the earth pulls them
  As an object falls toward earth, it speeds up: kinetic energy increases
- Objects with charge "fall" because other charges pull (or push) on them
  As a charge falls toward (away from) another charge, it speeds up: kinetic energy increases
- Where does this energy come from, in either case?
- Potential energy: energy stored by object, to be used or converted into kinetic energy (or another kind of potential energy) when required

Voltage

- Define electric potential or voltage
- voltage = potential energy per charge:

$$V = \frac{PE}{q}$$

- Units are volts: V = Joule/Coulomb

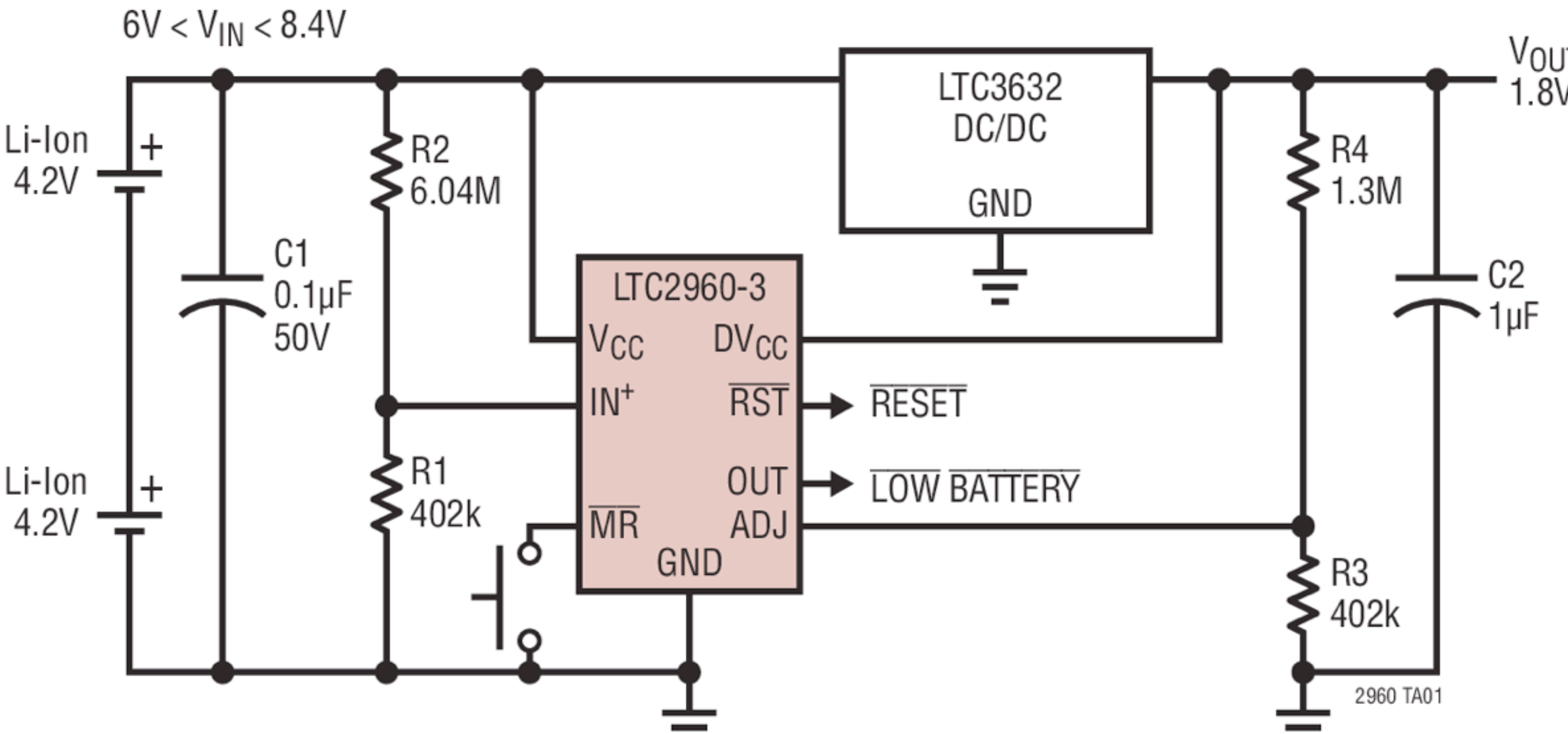
True or false:

That van de Graaff might develop thousands of volts!

Why Do We Need This?

- One good reason is that it makes sense: charge is quantized, so it is reasonable to think of energy per charge
- If we are moving electrons (current), then we are not dealing with a constant (static) amount of charge

Battery and Regulator Monitor



POWER-FAIL FALLING THRESHOLD = 6.410V
RESET FALLING THRESHOLD = 1.693V

One electron, one Joule of energy. Voltage?

A) Zero. One electron is too small to have any voltage.

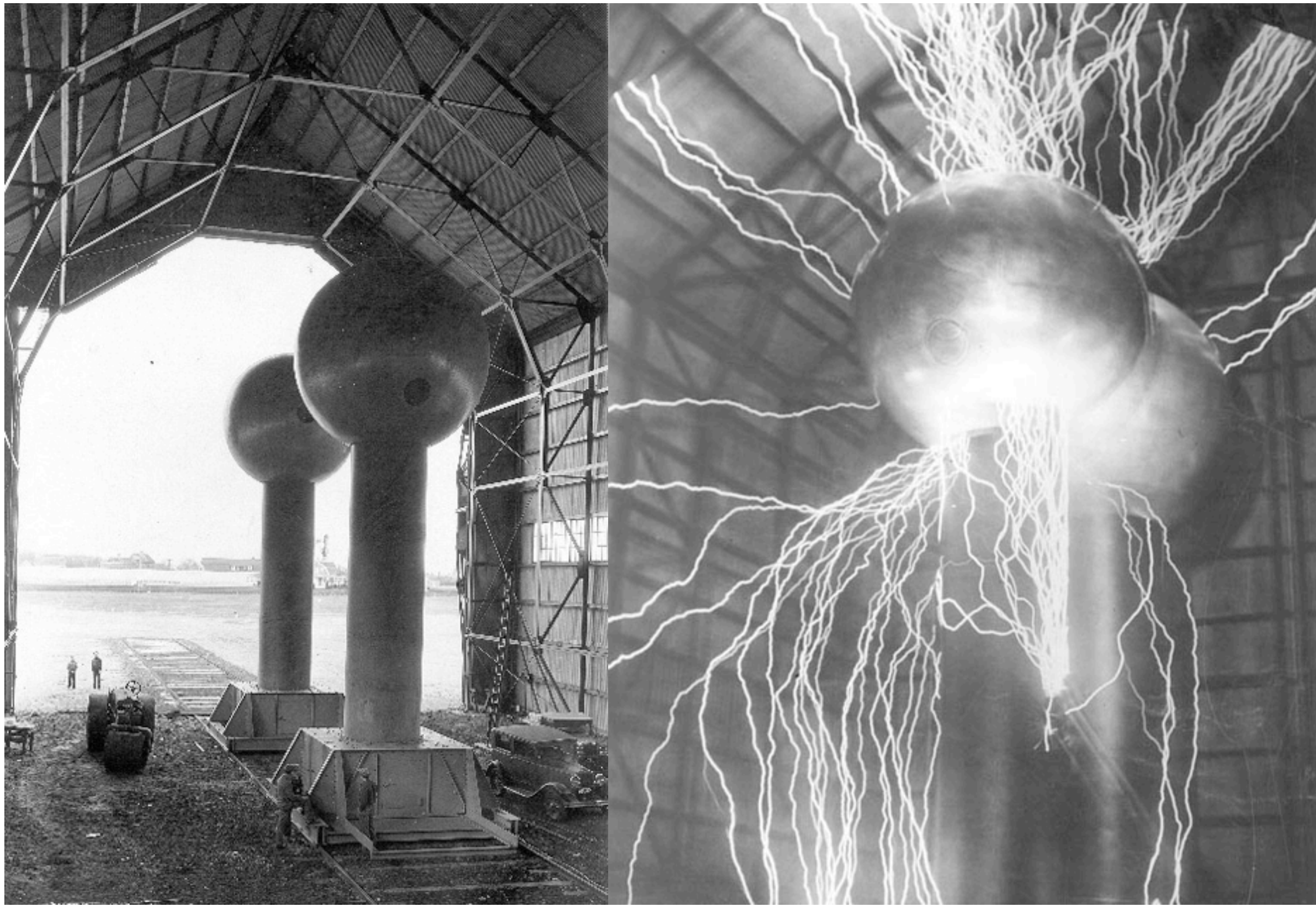
B) 1.6×10^{-19} V

C) 6.25×10^{18} V

D) Infinity!

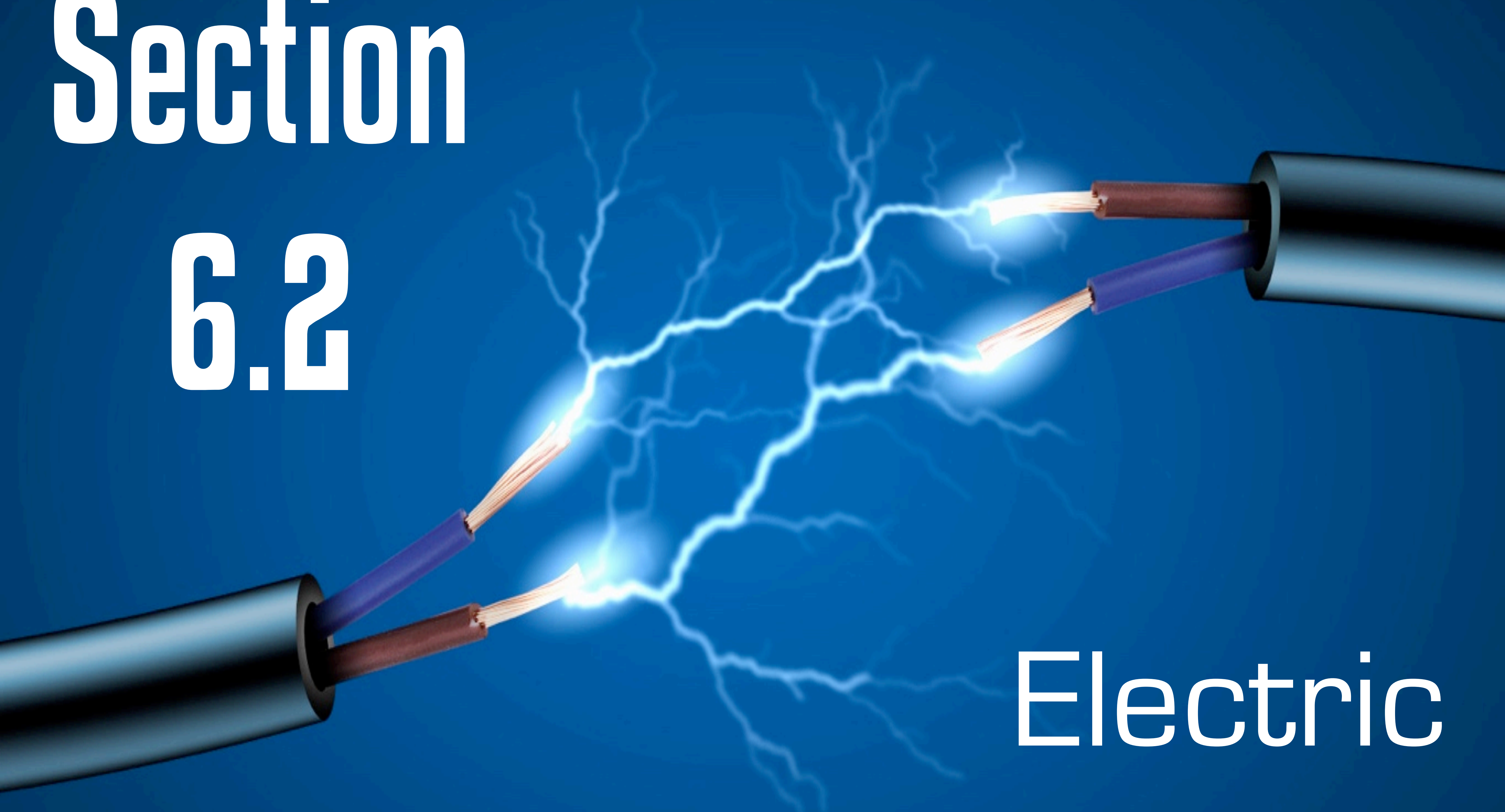
$$PE = 1\text{J}$$
$$q = 1.6 \times 10^{-19}\text{C}$$

$$V = \frac{PE}{q} = \frac{1\text{J}}{1.6 \times 10^{-19}\text{C}}$$



Giant van De Graaff, 1933 (built at MIT)

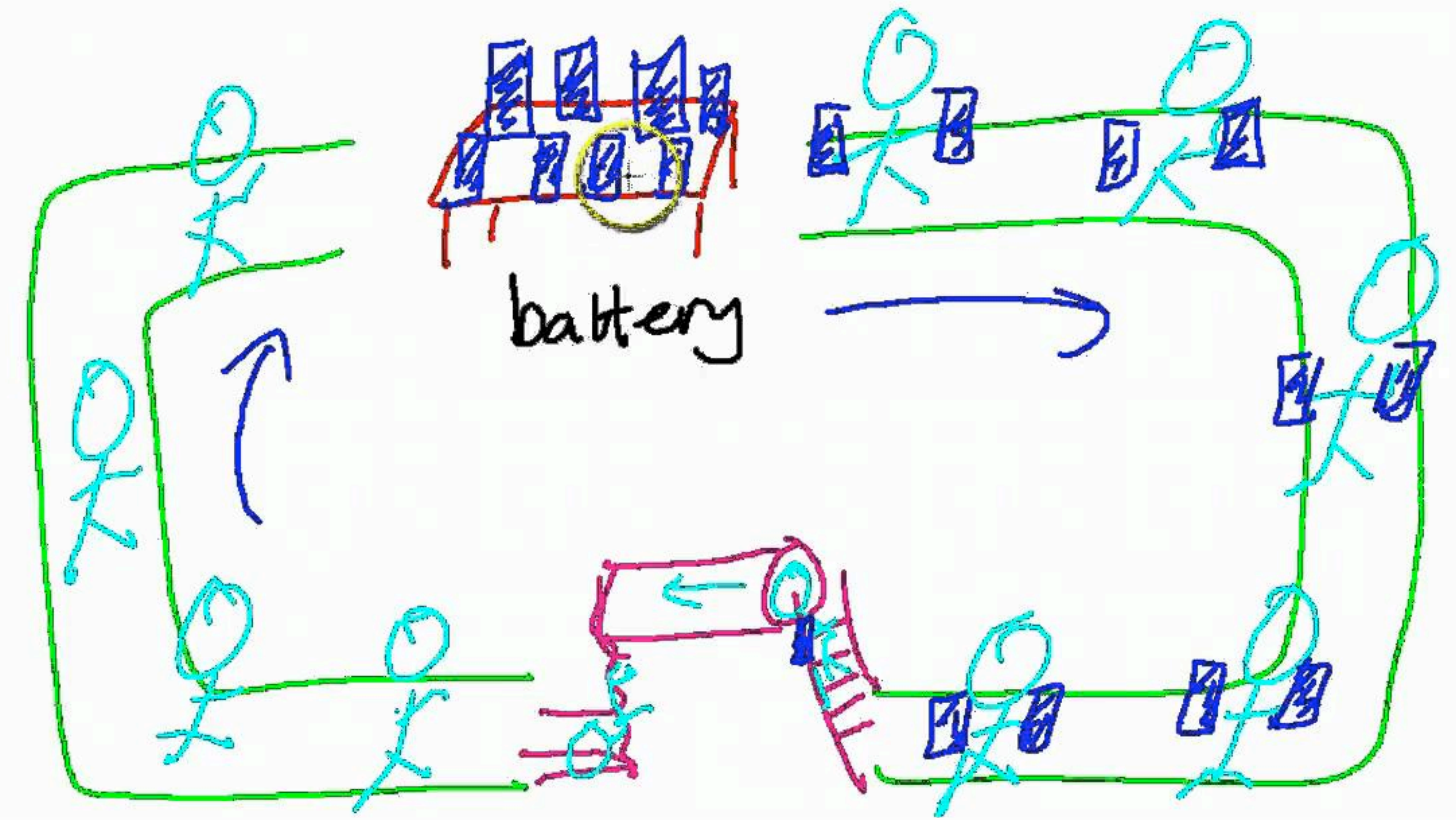
Section 6.2



Electric Current

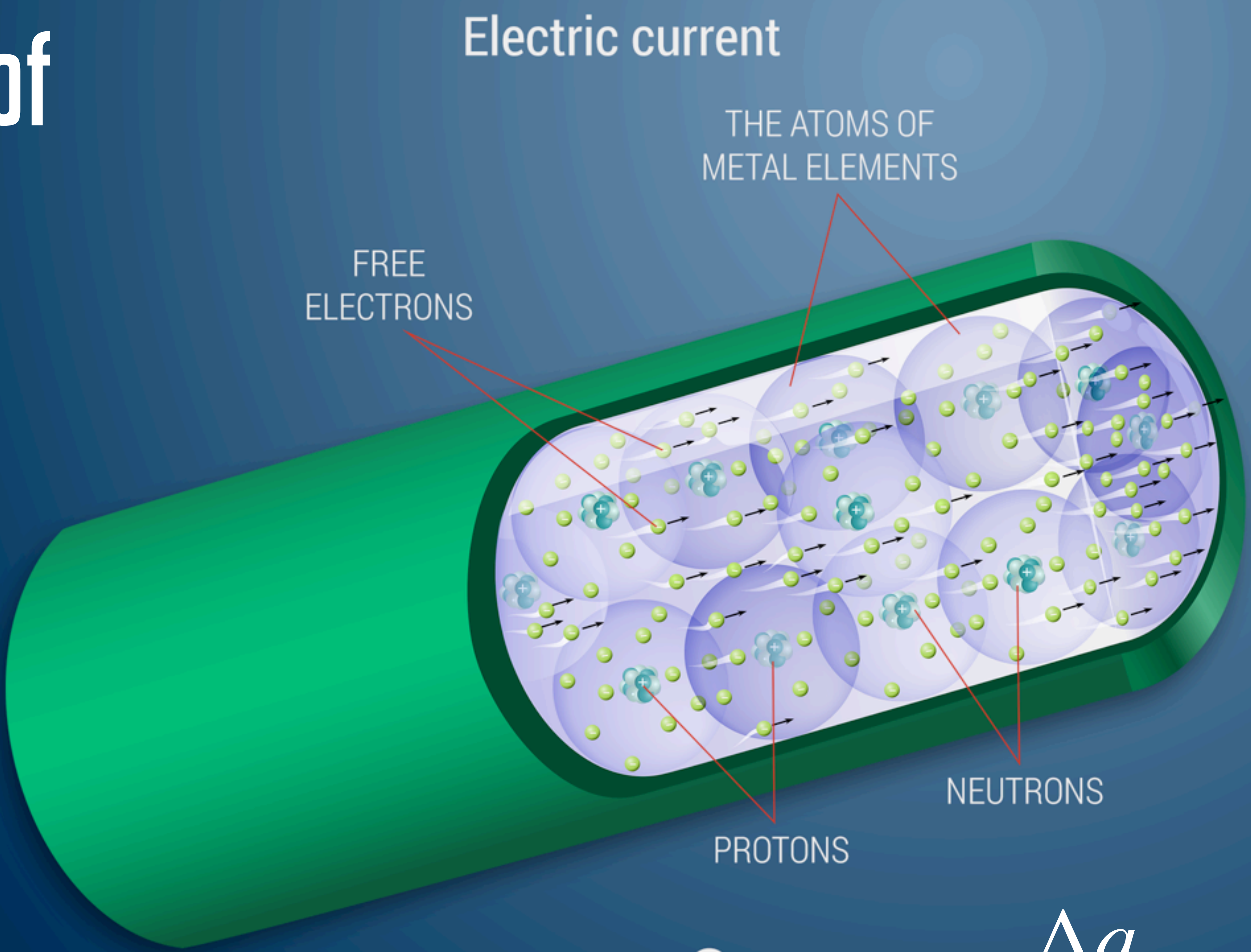
The Electric Circuit

- To make electrons flow (current), you have to give the a reason (a potential difference)
- This is still the work-energy theorem!
- Battery (voltage source) = pump!



The Nature of Current

- Time rate of change of charge
- Counting the number of charges per time, not how fast they are moving
- Unit: Ampere = Coulomb/sec



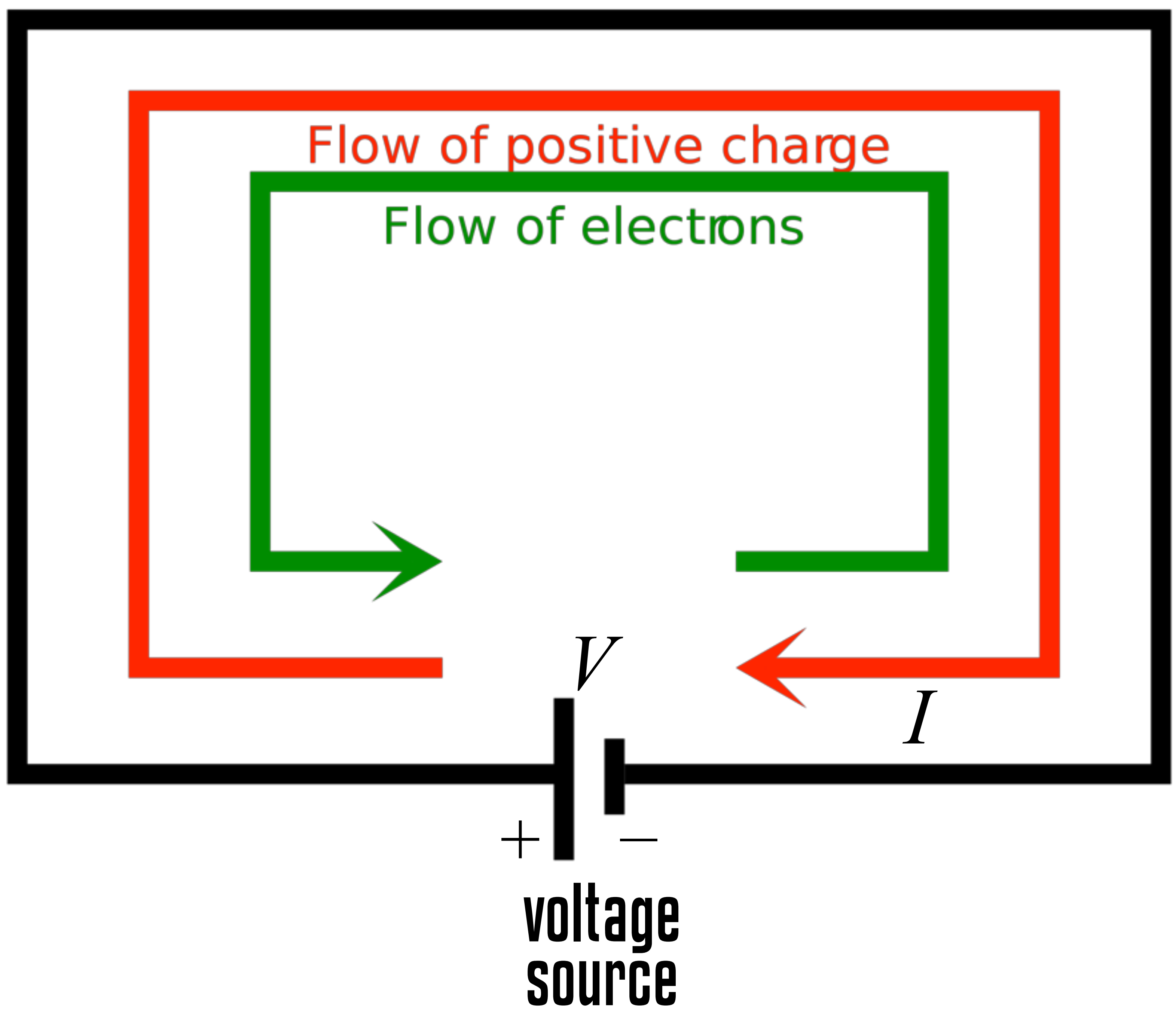
$$1A = 1\frac{C}{s}$$

A - ampere (electric current)
C - coulomb (electric charge)
s - second

$$I = \frac{\Delta q}{\Delta t}$$

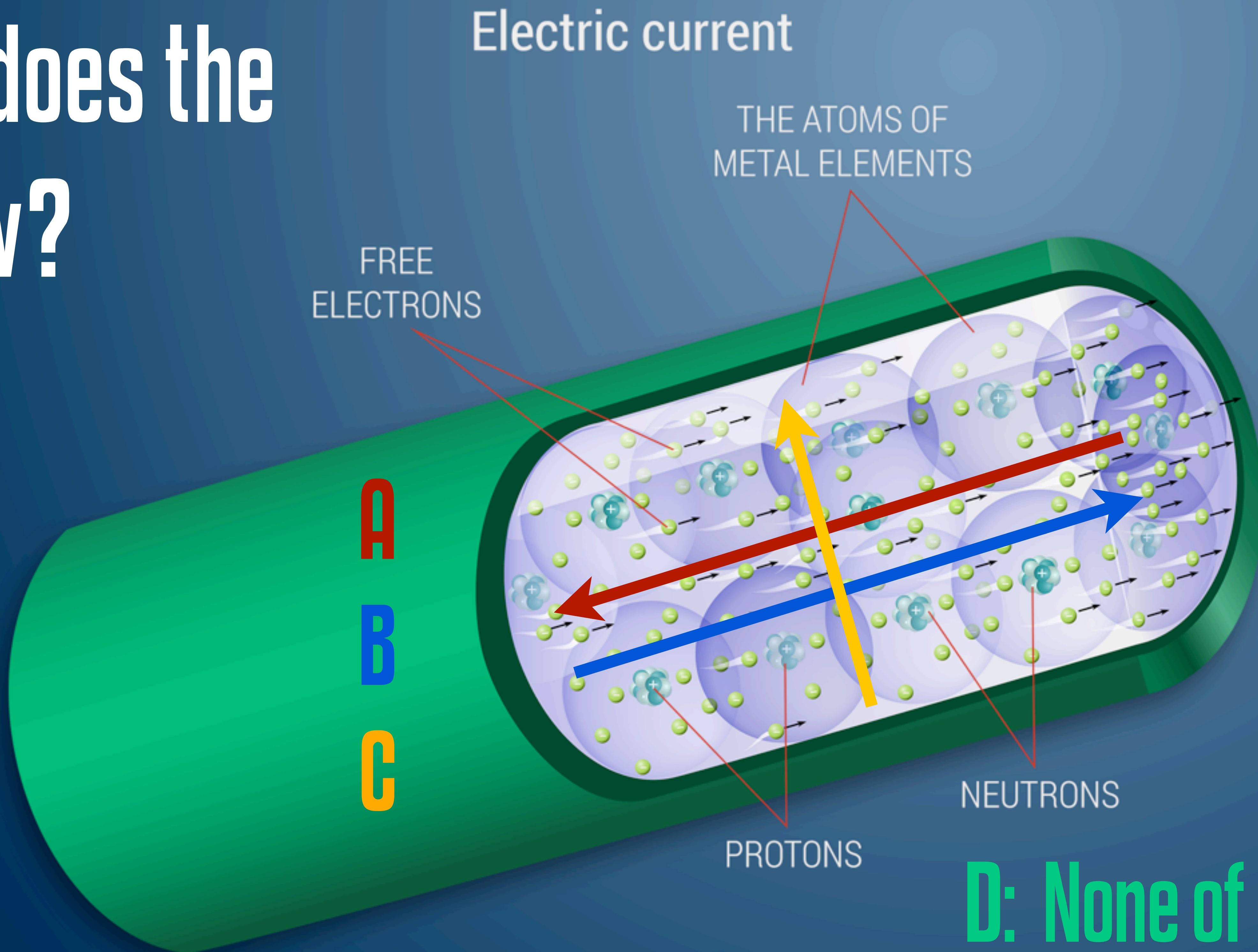
Sign Convention

- The convention for current is the direction of the motion of positive charge
- In solid conductors: electrons are passed from atom to atom (disclaimers apply!)
- YOU ARE NOT PULLING PROTONS OUT OF ANY NUCLEI!
- Electrons move from the negative to the positive (low to high) terminal of the voltage source (– charge falls up)
- Current flows from the positive to the negative (high to low) terminal of the voltage source (+ charge falls down)



Which way does the current flow?

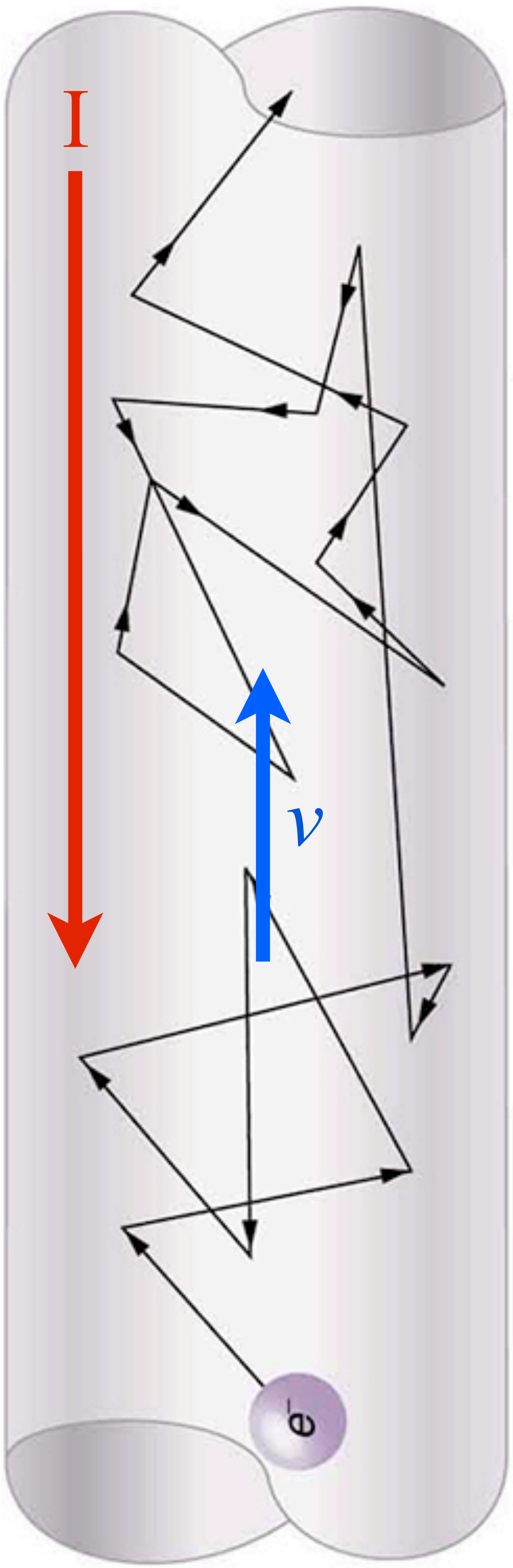
Choose the arrow which represents the sign convention for (+) current!



$$1A = 1\frac{C}{s}$$

A - ampere (electric current)
C - coulomb (electric charge)
s - second

D: None of these arrows is correct!



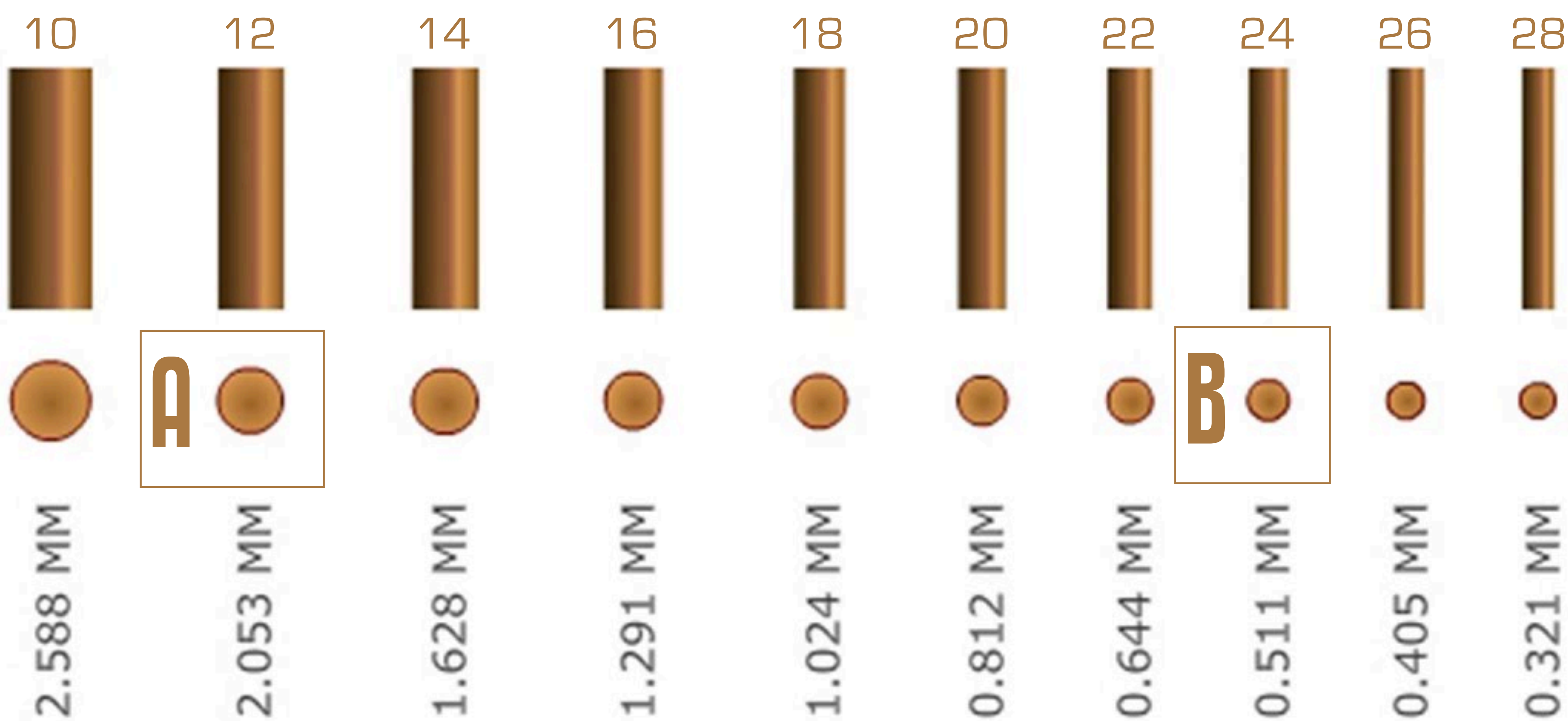
About Those Disclaimers...

- Direct current: electrons passed form atom to atom–locally! They do not pour out of one battery terminal, race around a circuit, then pour back into the other terminal!
- Drift velocity: electrons move significantly slower than the speed of light!
- Alternating current: electrons oscillate in place–they don't have to migrate at all!

Electrical Resistance

- Electrons encounter resistance as you try to move them through a potential difference
- Material makes a difference: typically metals have lower resistance
- Geometry makes a difference: longer wire makes more resistance; wider wire makes less resistance
- Temperature makes a difference: higher temperature, higher resistance

Two wires: same material, same length, same temperature. Which one has greater resistance?

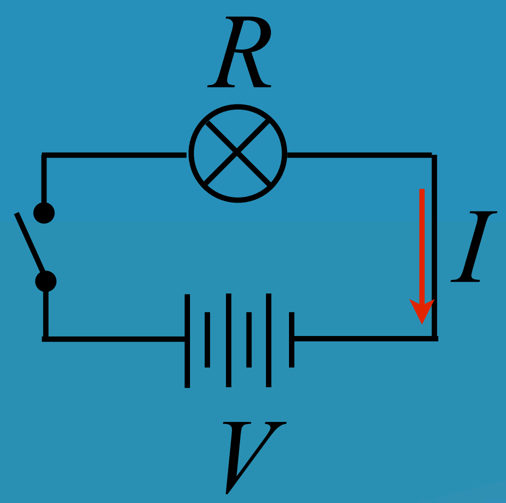


A) Wire A

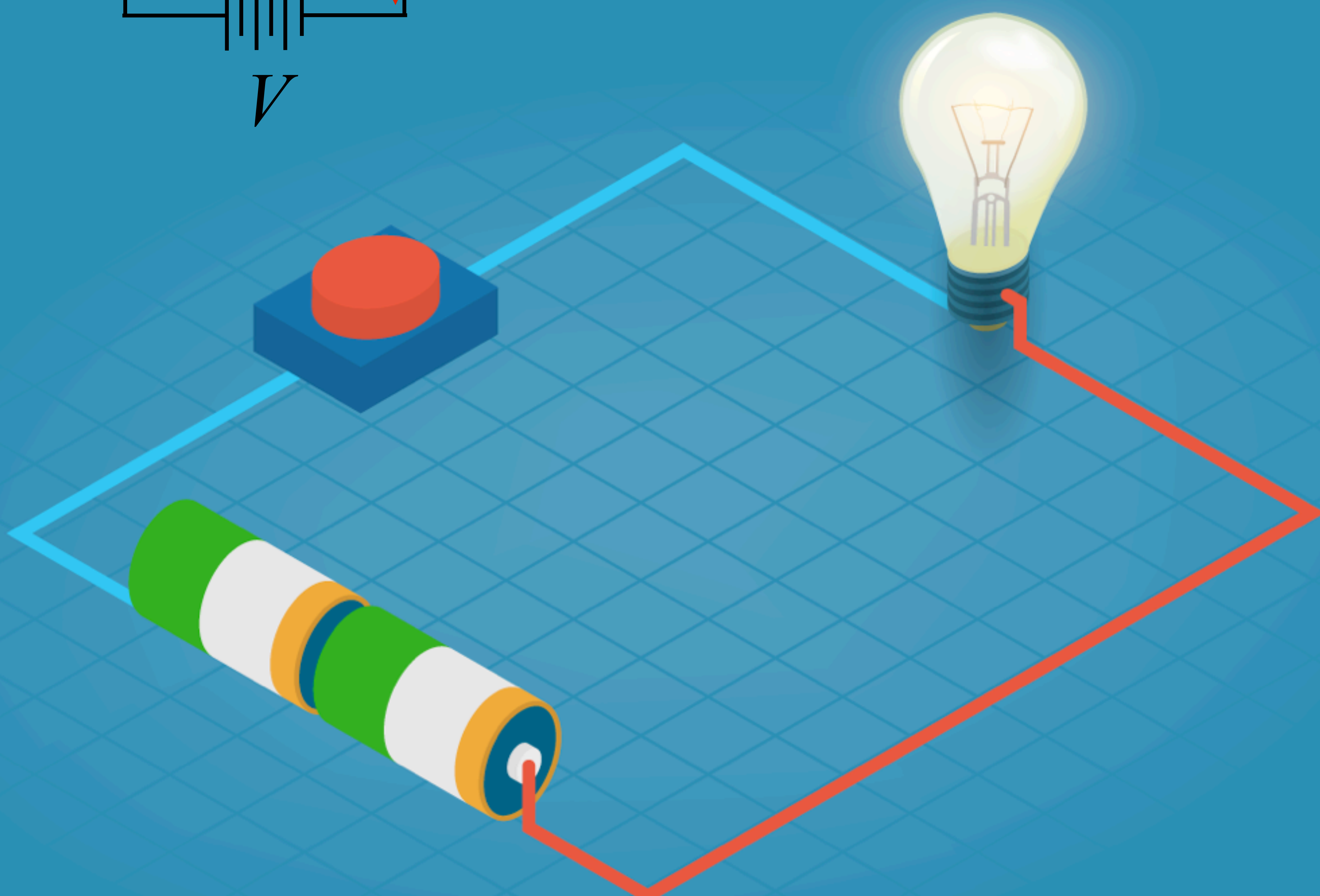
B) Wire B

C) Both wires have the same resistance!

Current, Voltage, and Resistance

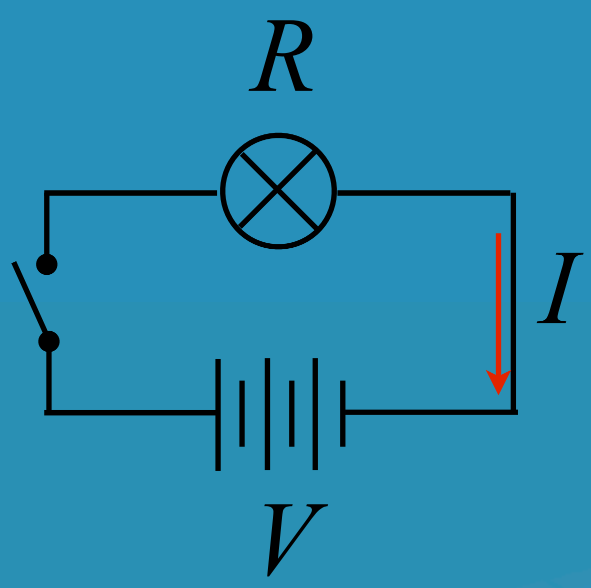


$V = IR$ $\quad I = \dfrac{V}{R}$ $\quad R = \dfrac{V}{I}$



- The greater the resistance, the more work you have to do to move a given quantity of charge
- The greater the resistance, the less charge you can move by doing a given amount of work
- Ohm's Law: $V = IR$
- Unit of resistance Ohm = Volt/Amp (Ω = V/A)

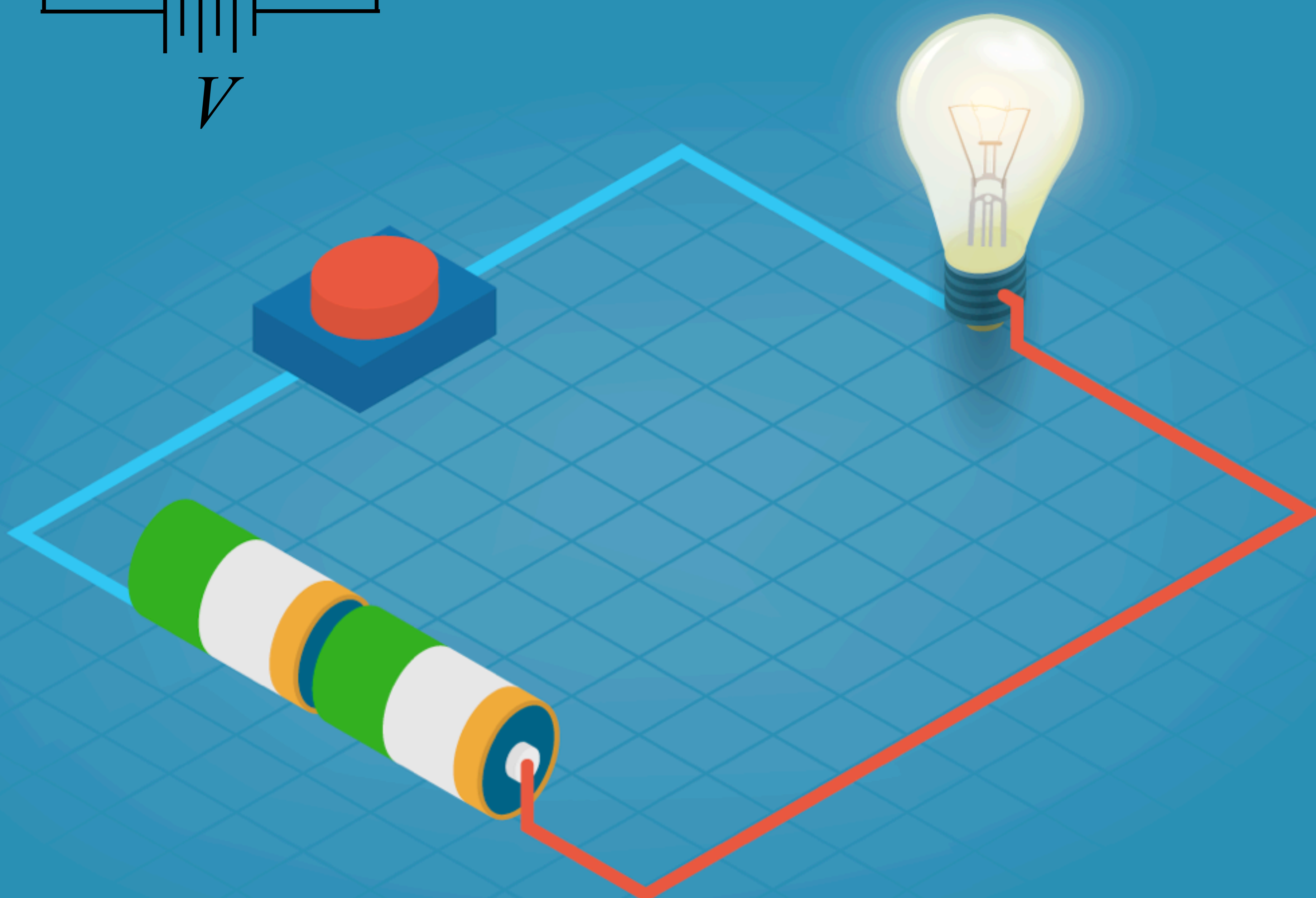
A 9V battery is wired into a circuit with a 6Ω bulb. What is the current?



$$V = IR$$

$$I = \frac{V}{R}$$

$$R = \frac{V}{I}$$



A) $I = 0\text{amp}$

B) $I = 0.7\text{amp}$

C) $I = 1.5\text{amp}$

D) $I = 6\text{amp}$

E) $I = 9\text{amp}$

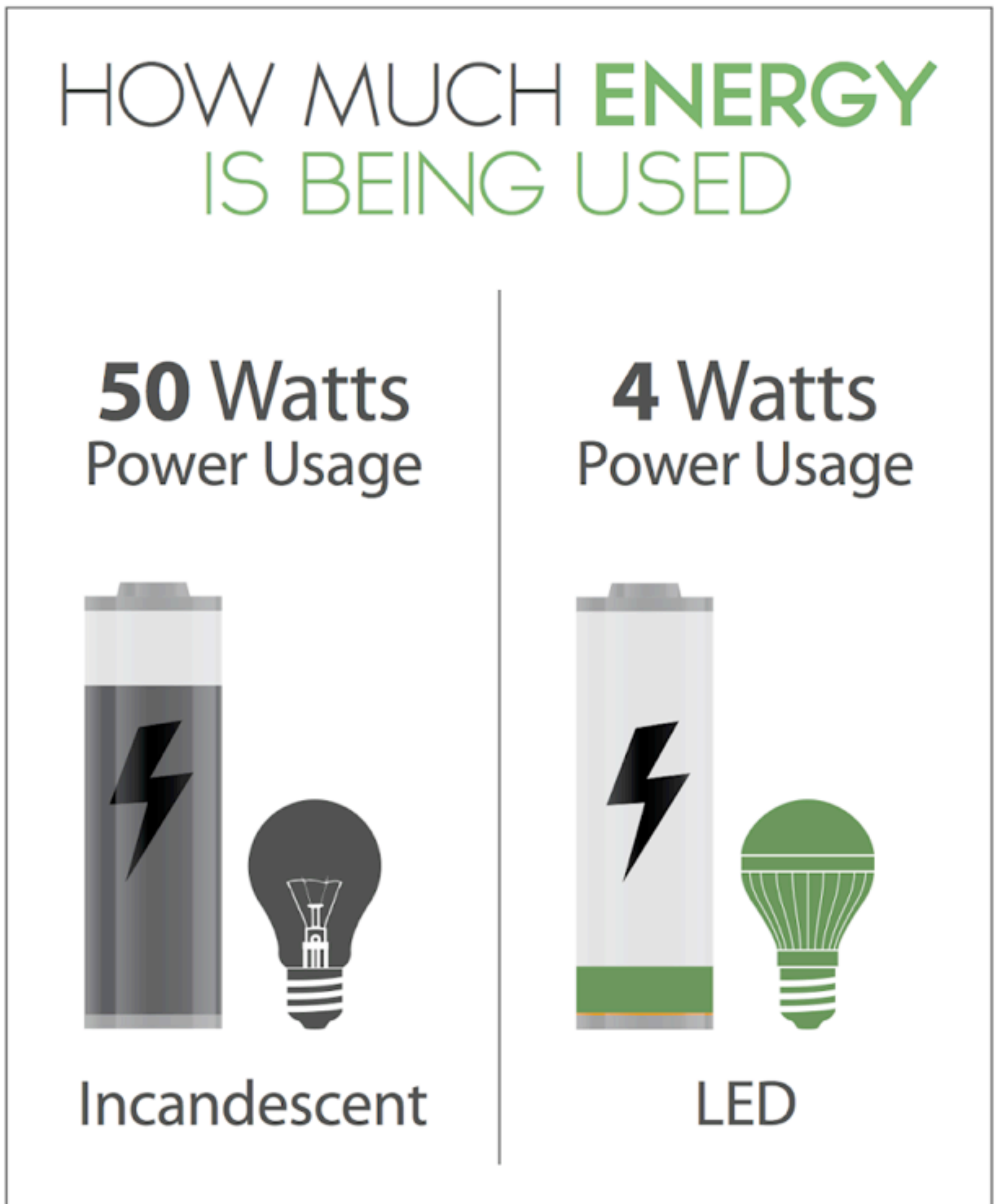
F) $I = 54\text{amp}$

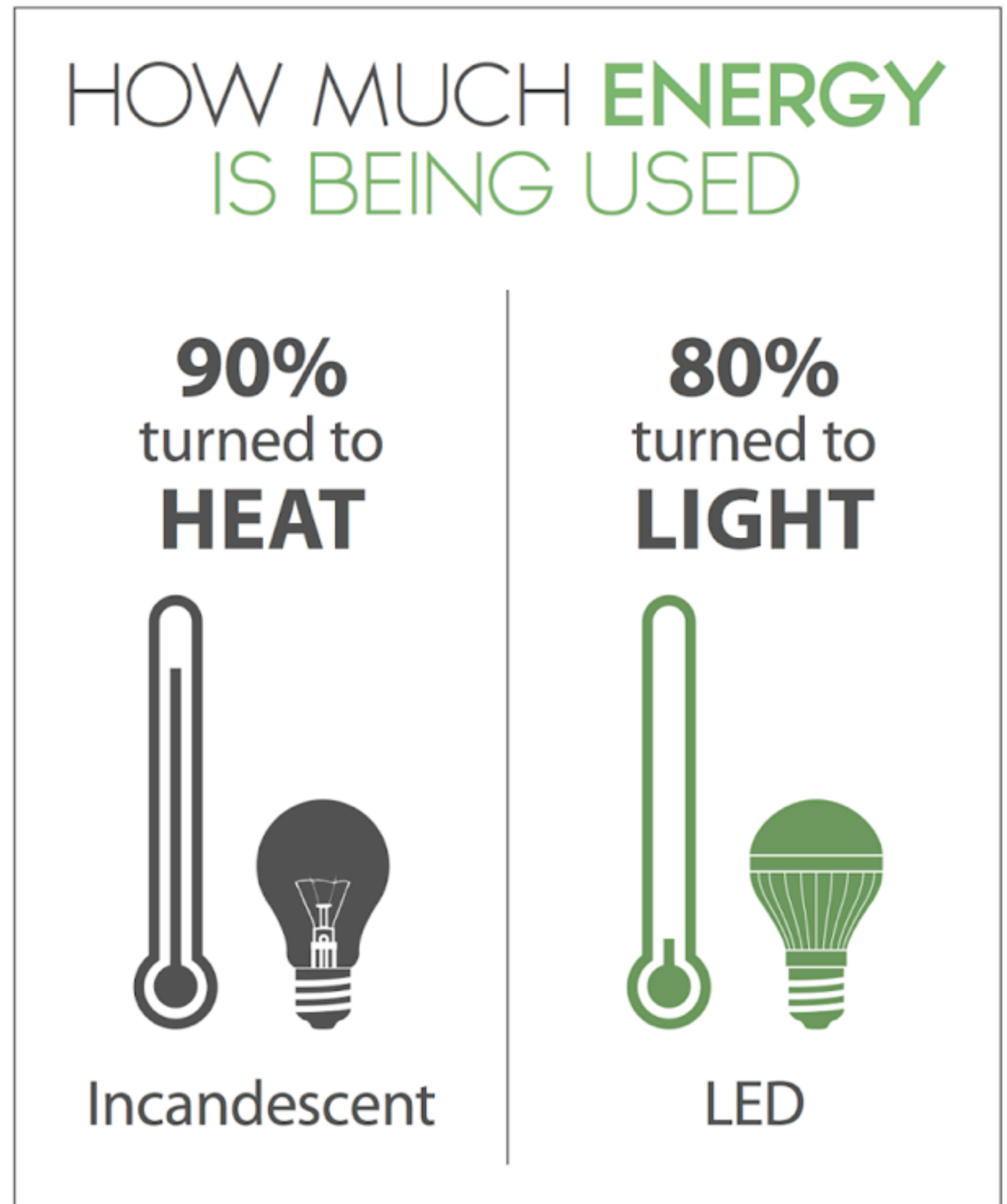
Electrical Power and Electrical Work

$$P=\frac{qV}{t}=\left(\frac{q}{t}\right)V=IV$$

$$P=IV=\left(\frac{V}{R}\right)V=V^2R$$

$$P=IV=I(IR)=I^2R$$





How many amps does an 1800W blow dryer draw?

Household voltage
$V = 120\text{V}$
Determine the amount of current drawn. Answer with two sig figs.

$$P = IV$$

What's the resistance of the 1800W blow dryer?

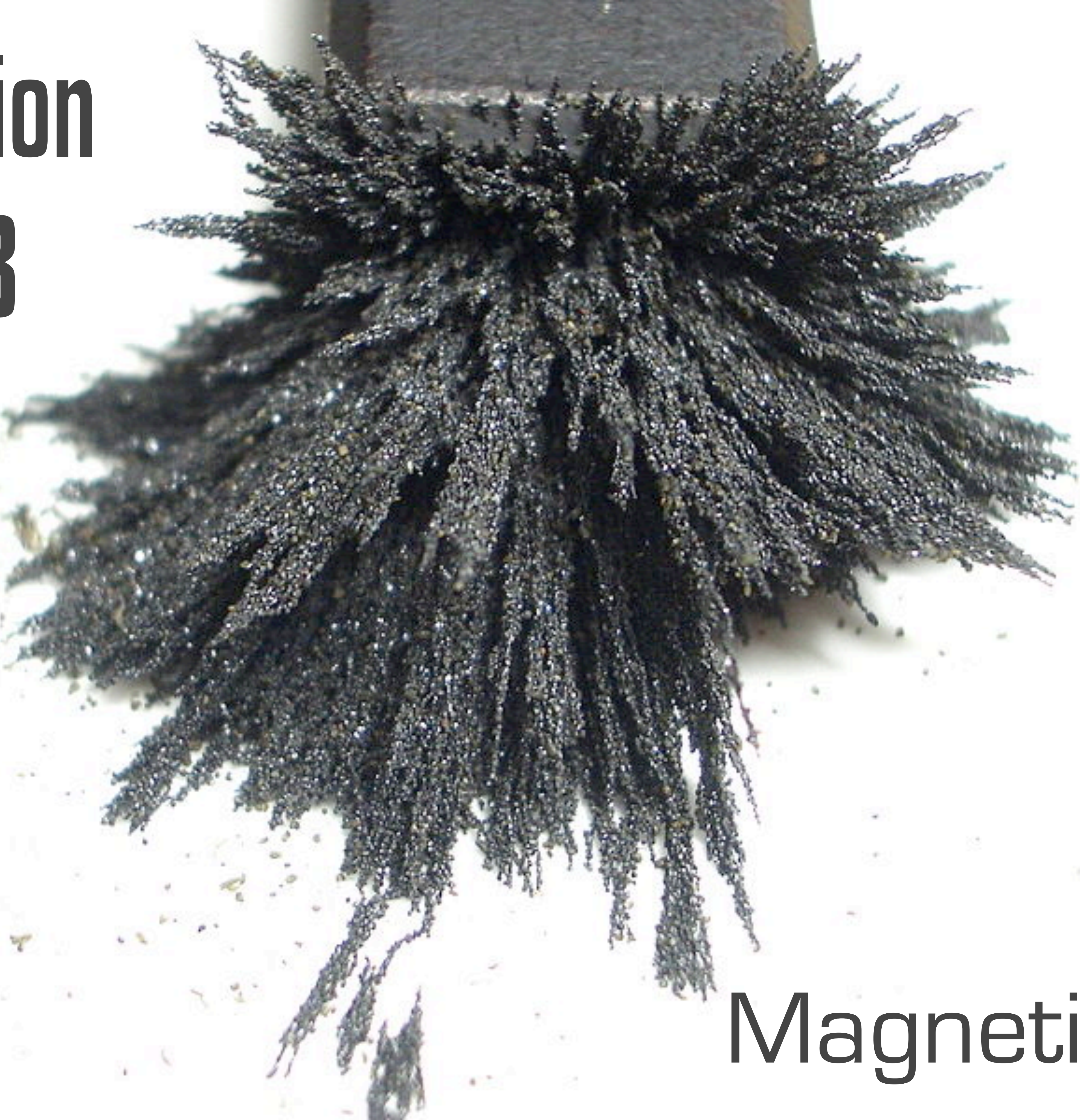
Household voltage

$V = 120\text{V}$

Determine the resistance. Answer to the nearest integer.

$$P = \frac{V^2}{R}$$

Section 6.3



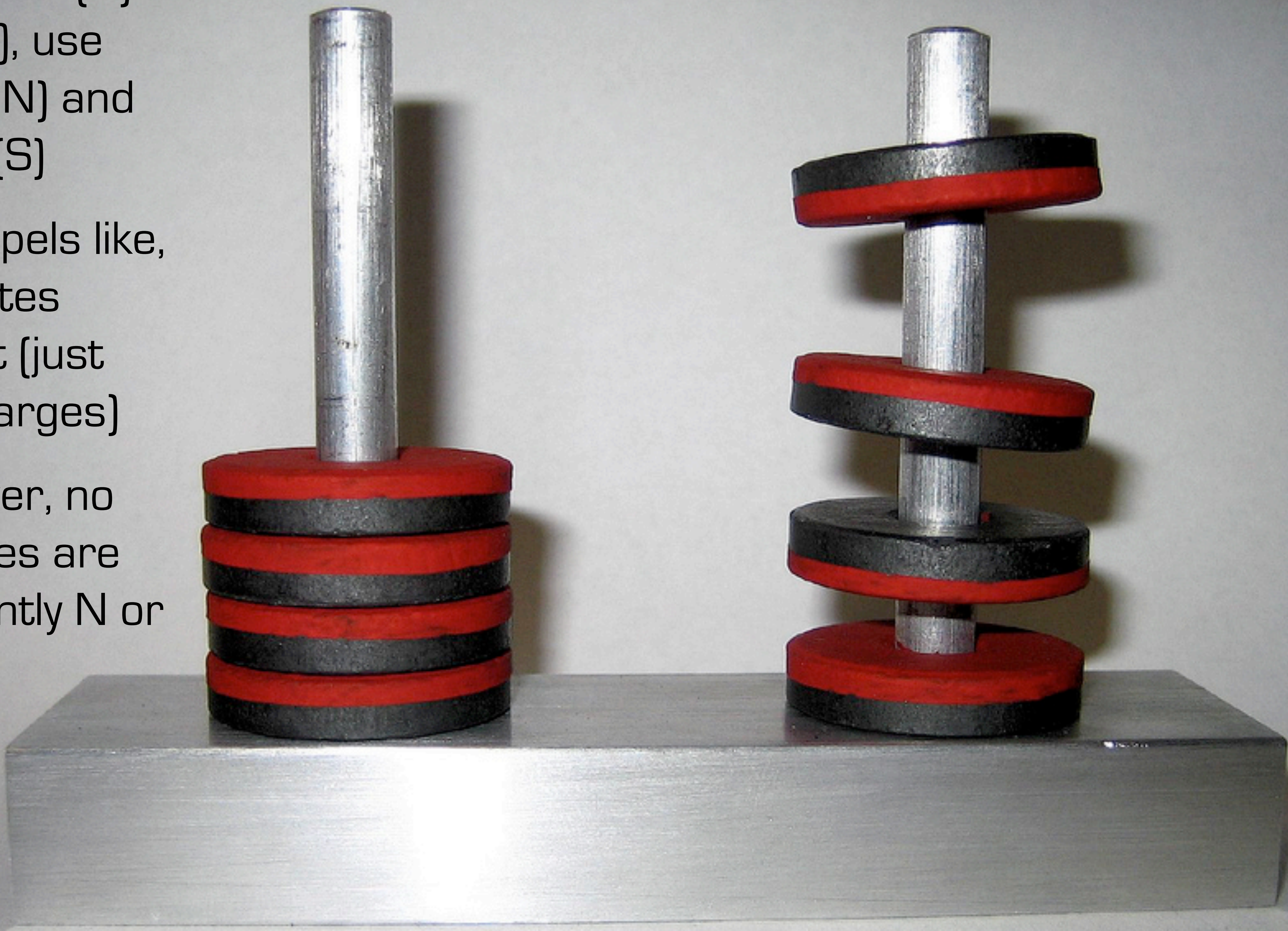
Magnetism

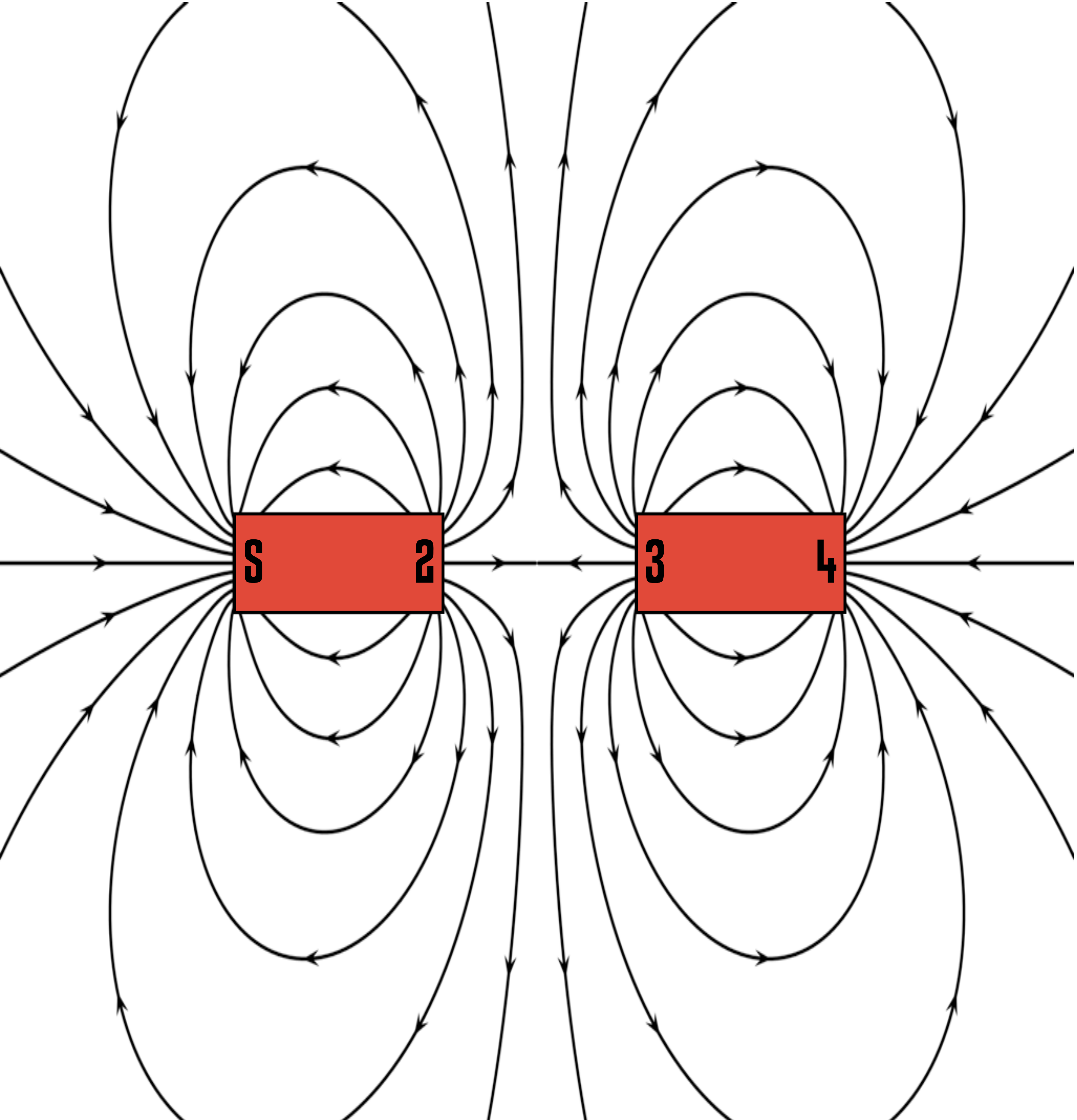
Only Some Things Are Magnetic

- Iron, nickel, cobalt: ferro-magnetic materials
- Most everything else: Not so much
- The punch line is all about the electrons!

Magnetic Poles

- Analogy to electric charge: Instead of (+) and (–), use north (N) and south (S)
- Like repels like, opposites attract (just like charges)
- However, no particles are inherently N or S





The pole labeled 4 is a south (S). Pole 3, then must be

A) North (N)

B) South (S)

C) Neither North nor South!

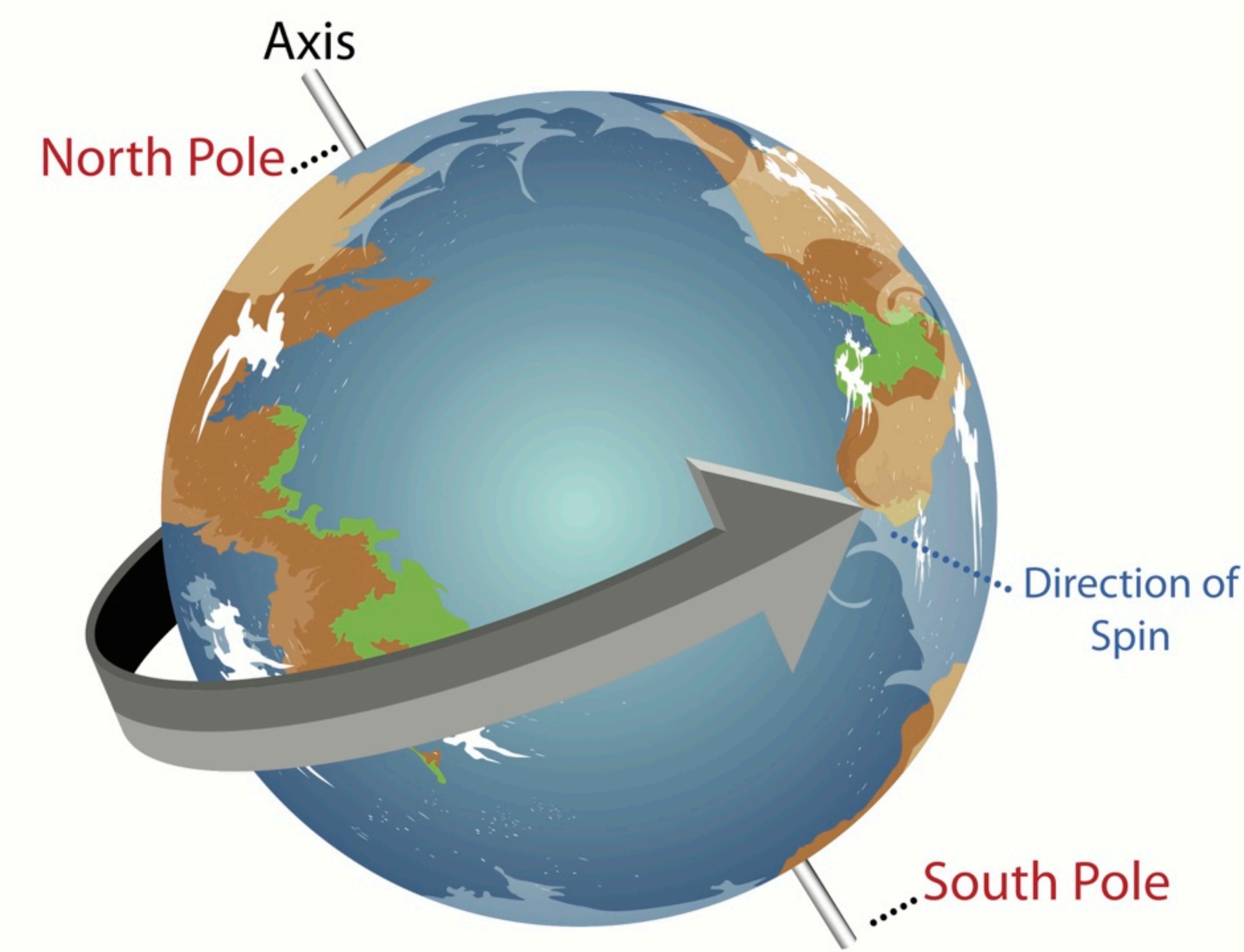
D) Could be either North or South!

E) No way to tell!

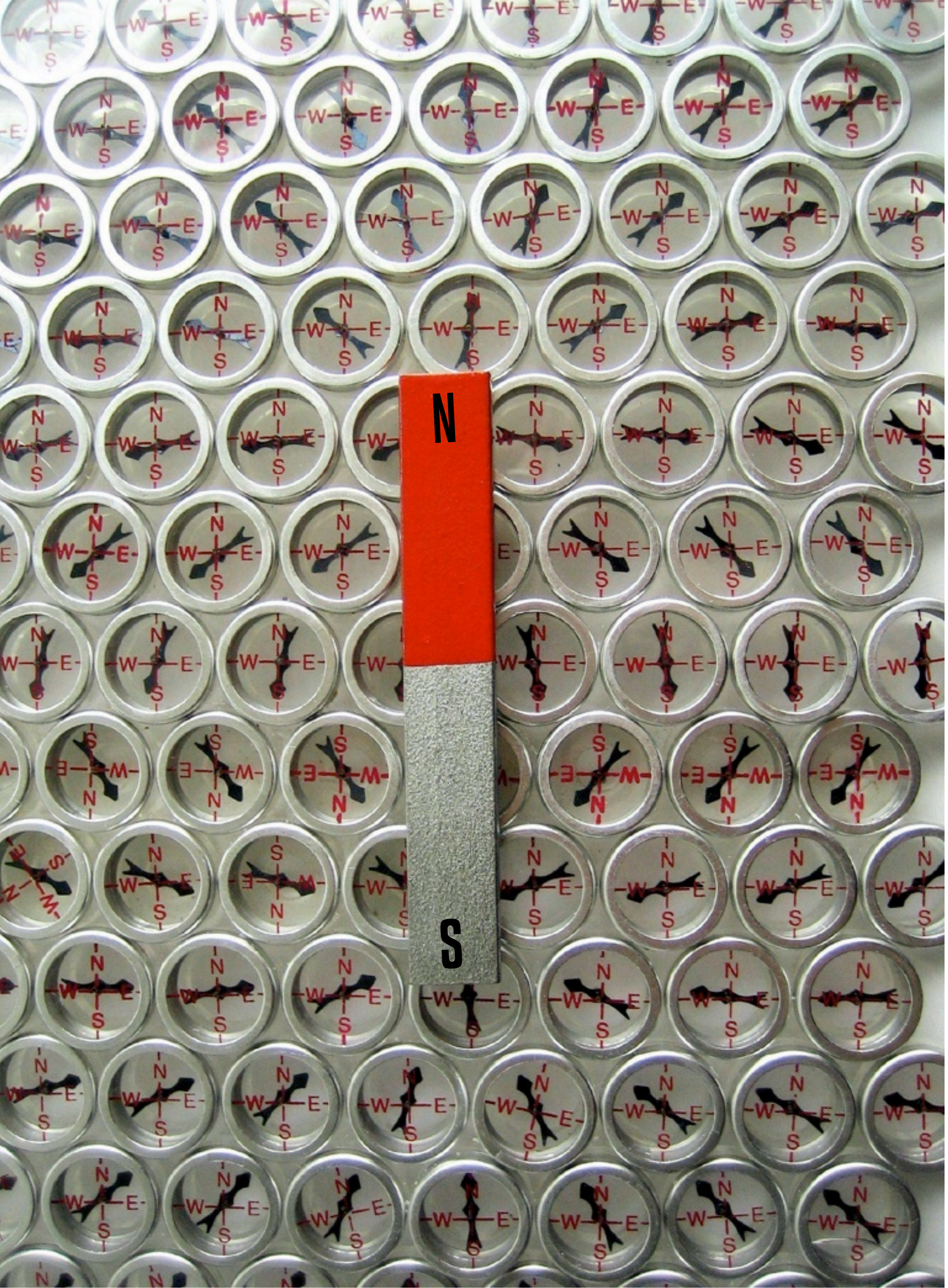
True or false?

You might have a magnet that has a single North pole, located at the exact center of the magnet.

Poles Always Come In Pairs



- Earth only spins in one direction
- If you look at it "top down," it appears to spin counterclockwise
- If you look at it "bottom up," it appears to spin clockwise
- The earth only spins in one direction, but it has two poles: North and South
- Same thing with magnets: an electron only spins in one direction, but has two poles

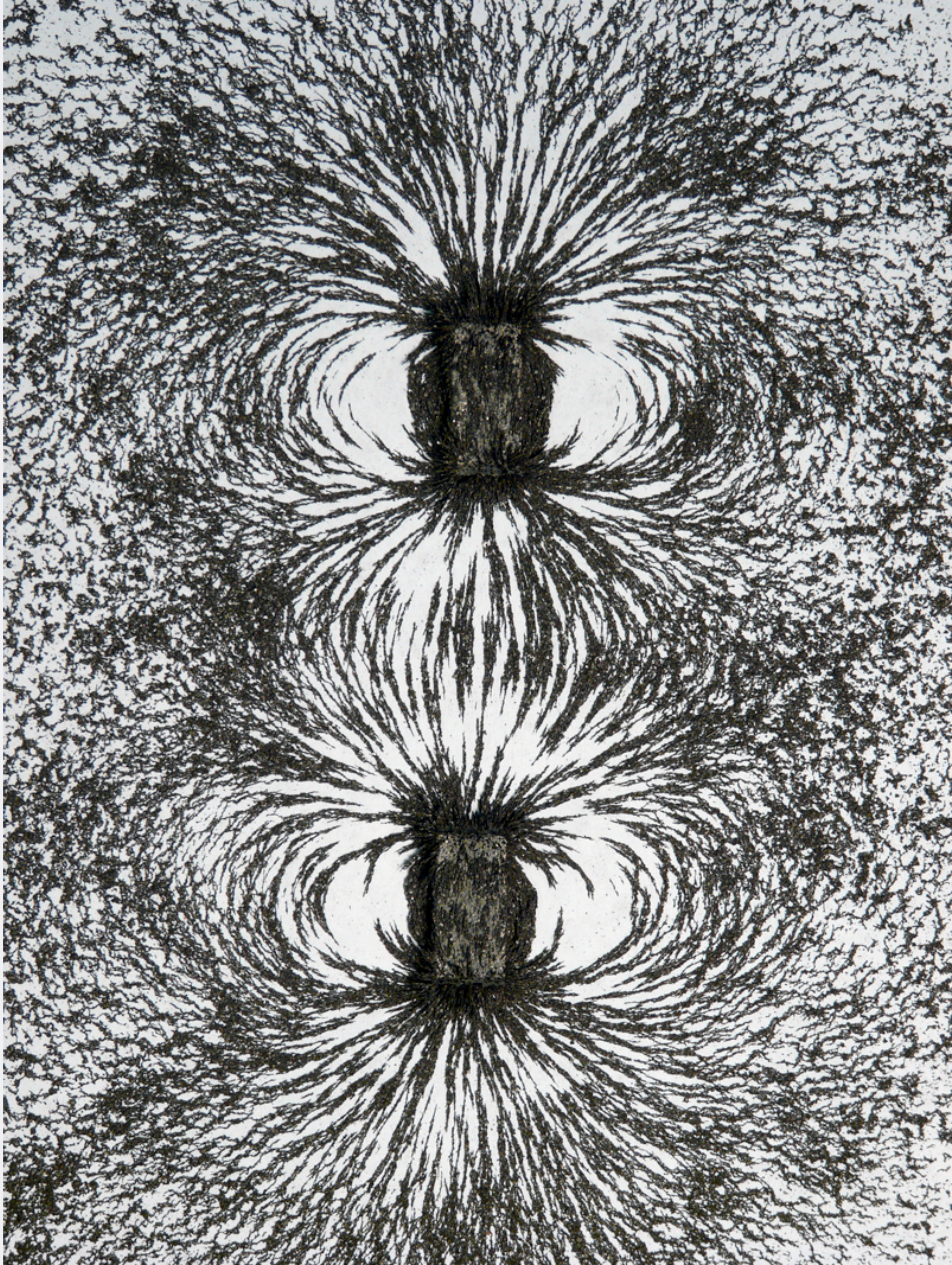


Magnetic Fields

- Magnetic force is an action-at-a-distance force
- Magnetic Field B: describe the behavior of a test magnet (like a compass) placed in the vicinity of a fixed magnet
- Field lines directed away from the North and toward the South pole of the fixed magnet

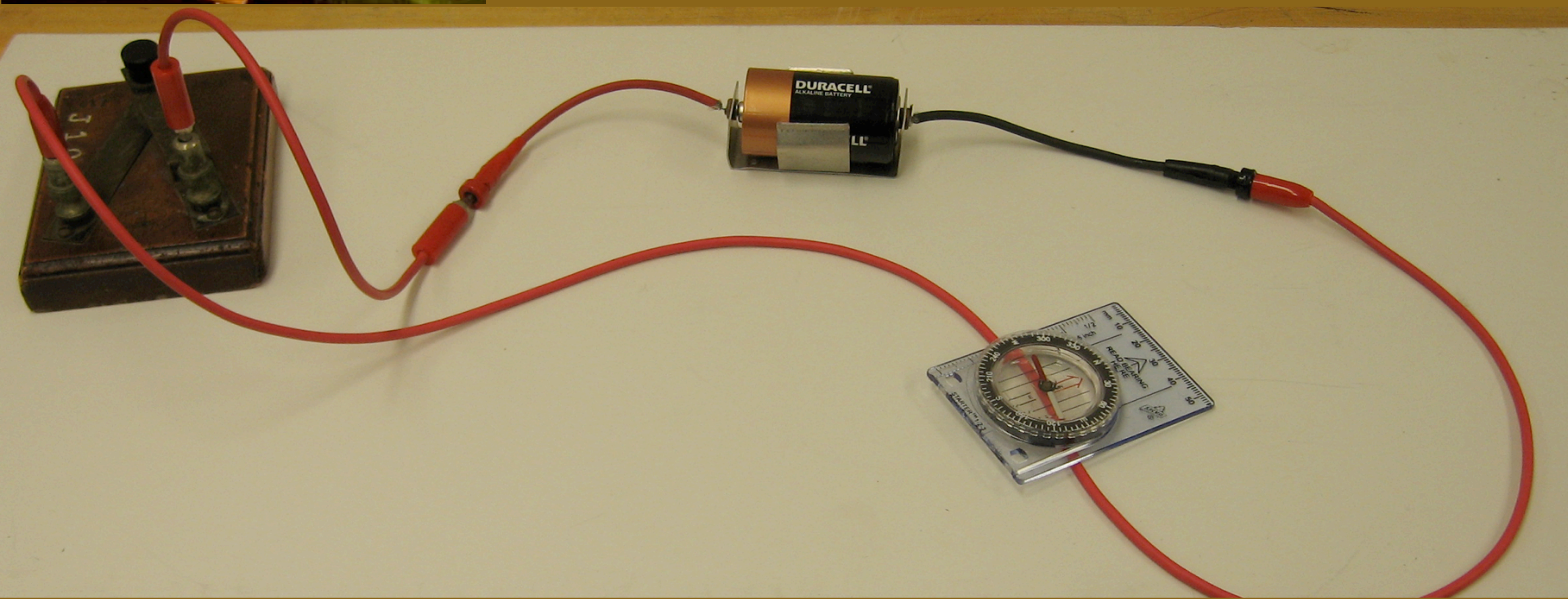
The Source of Magnetic Fields

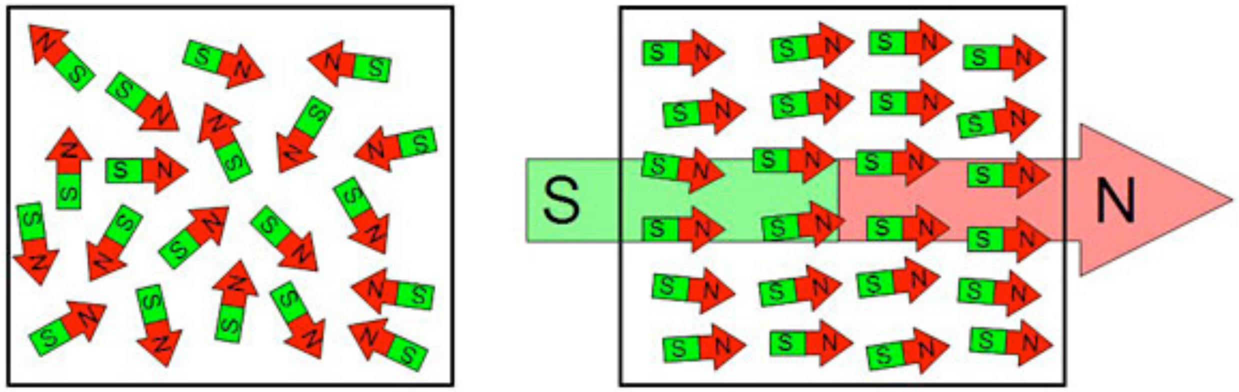
- Electrostatic Force: Force between charged particles at rest. Exists because the charges themselves exist
- Magnetic Force: Force between charged particles in motion. Any time you move a charged particle, you will create a magnetic force
- Since both are directly because of charge, these forces are related—but not the same thing!



Oersted's Eureka

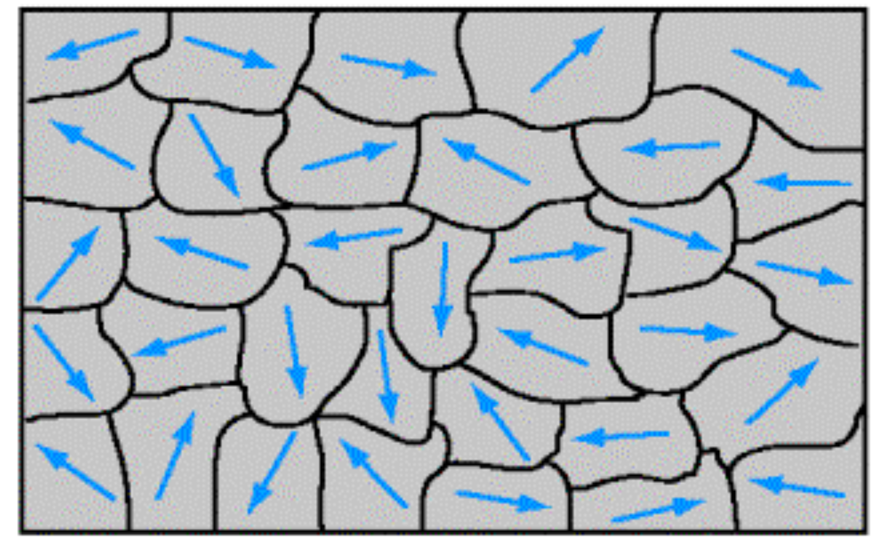
- Observation that a magnetic field exerts a force on a current carrying wire
- Observation that a current carrying wire creates its own magnetic field
- Any moving charge creates a magnetic field!



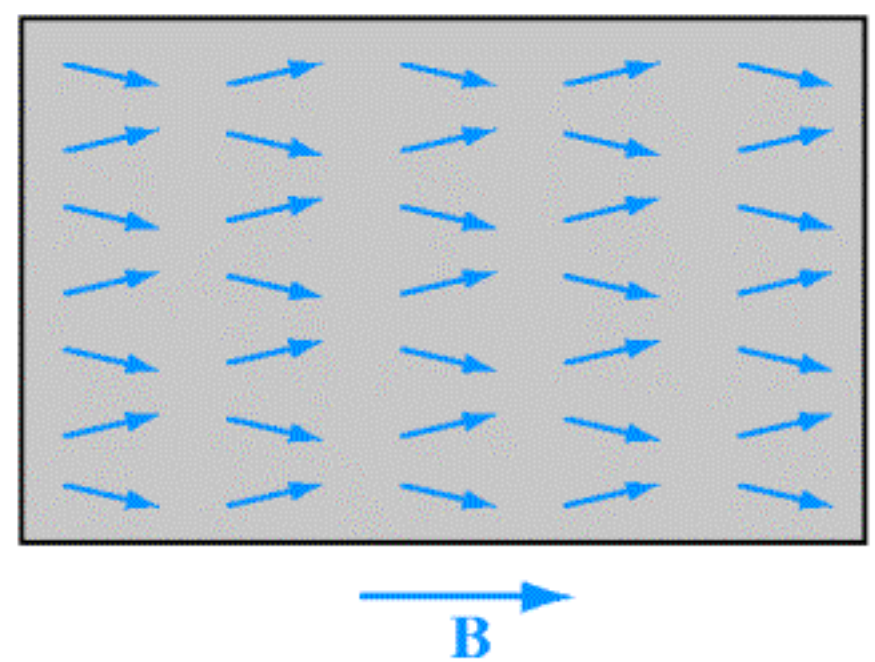


Permanent Magnets

- Your fridge magnets are not carrying currents!
- Other electron motions: orbit, spin (definitely not the same as planets, but a useful visual image)
- Magnetic domain: region where electron spins are in alignment creates magnetic field

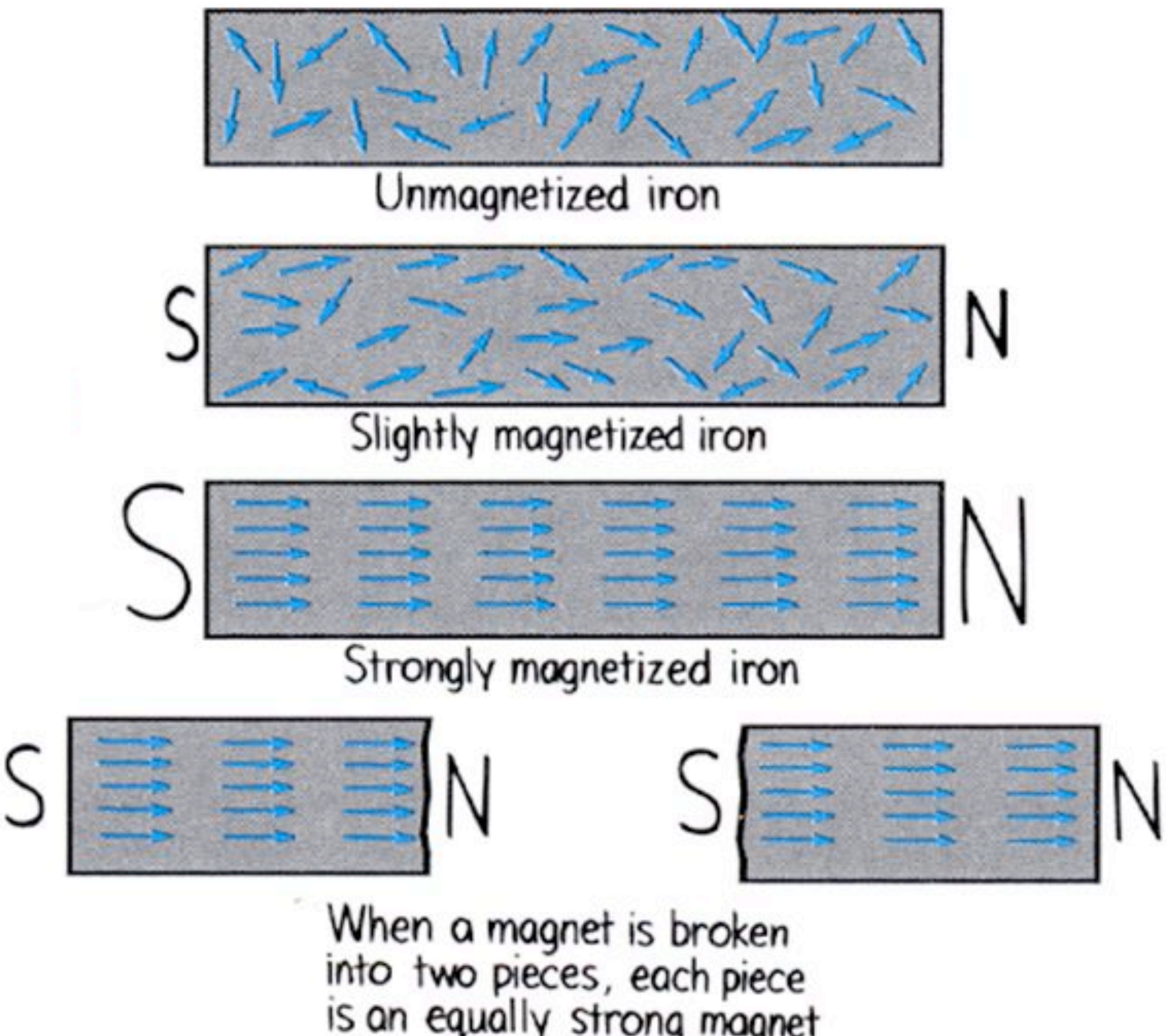


(a) Unmagnetized domains



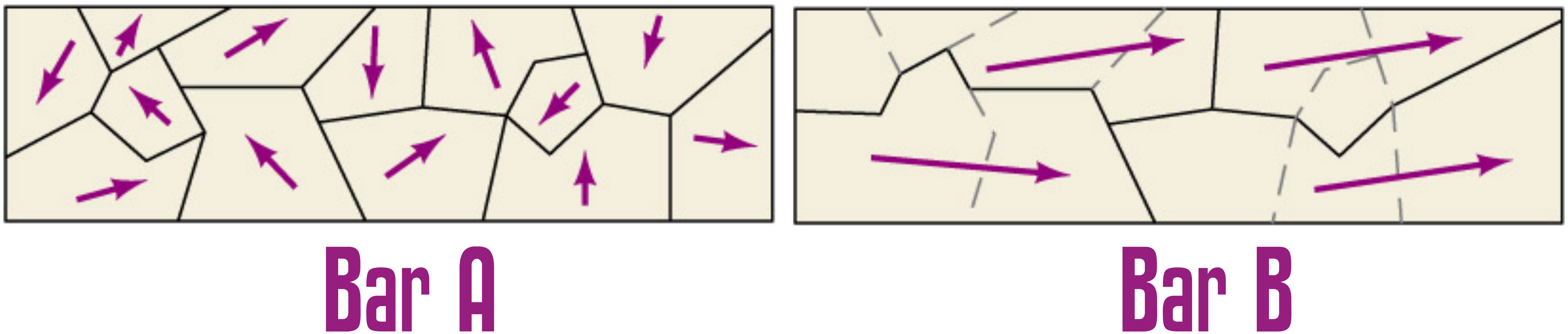
(b) Magnetized domains

Not Every Piece of Iron Is a Magnet!



- Because the magnetic domains are randomly aligned, and cancel each other out
- Magnetic domain: localized region within the bulk matter where spins are aligned
- The greater the alignment, the stronger the magnetic field

Which piece of iron is the bar magnet?



A) Bar A.

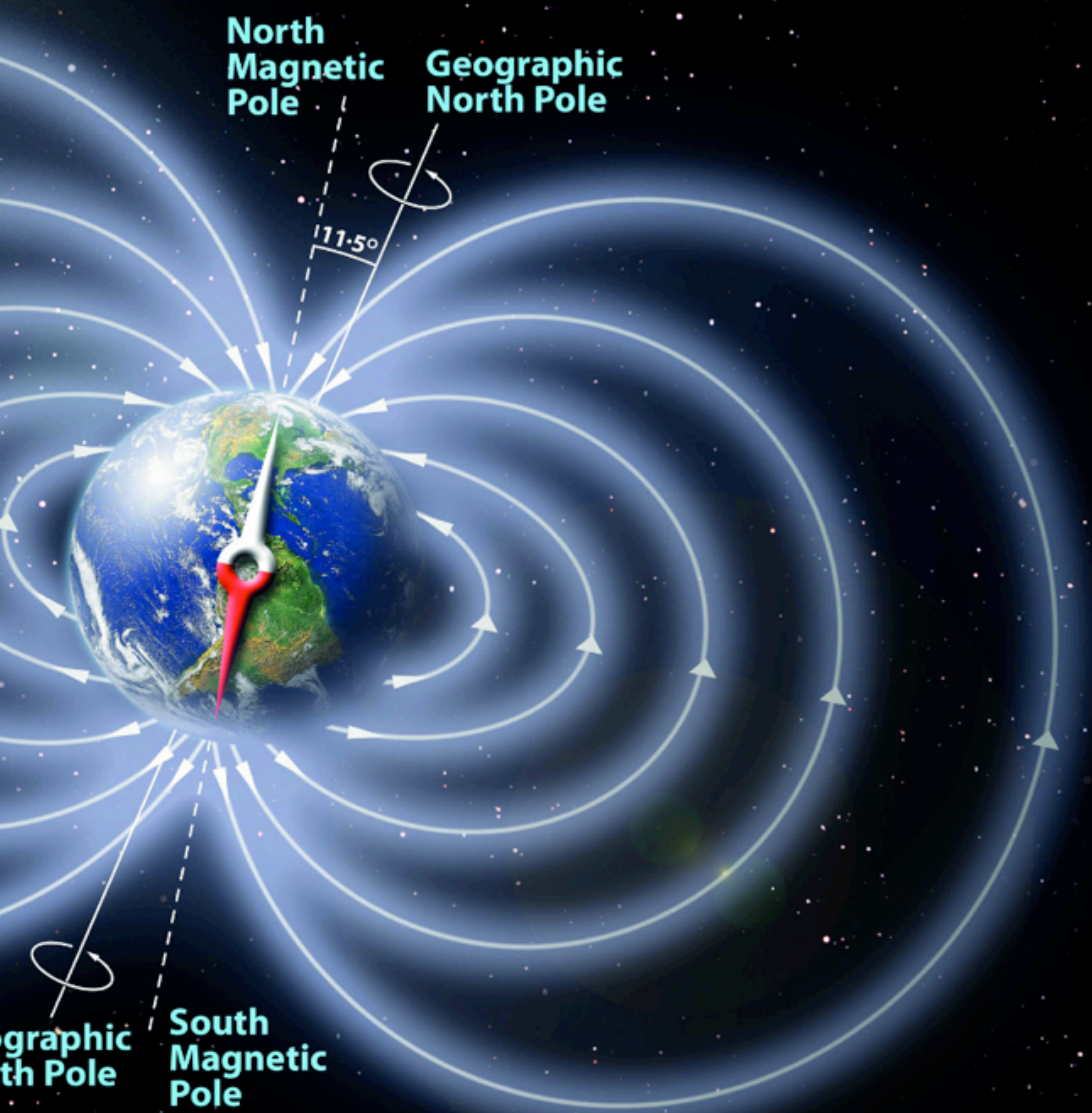
B) Bar B.

C) Both bars are strong magnets.

D) Neither bar is magnetic at all!

The Earth's Magnetic Field

- Not a permanent magnet: magnetic dynamo
- Field generated continuously by spinning the fluid iron-nickel outer core
- Field is offset: rotational axis ≠ magnetic axis!
- N and S poles have been known to reverse: who knows why?



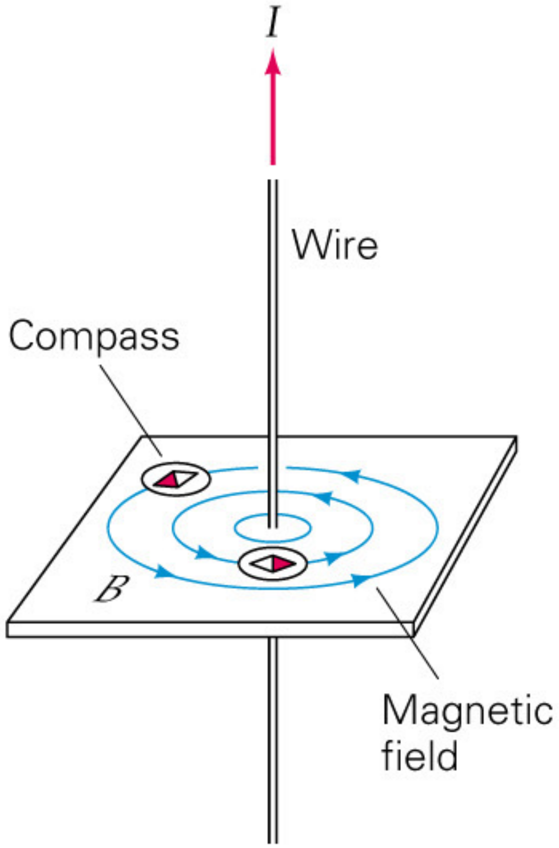
Peter Reid (peter.reid@ed.ac.uk), 2009

Section 6.4

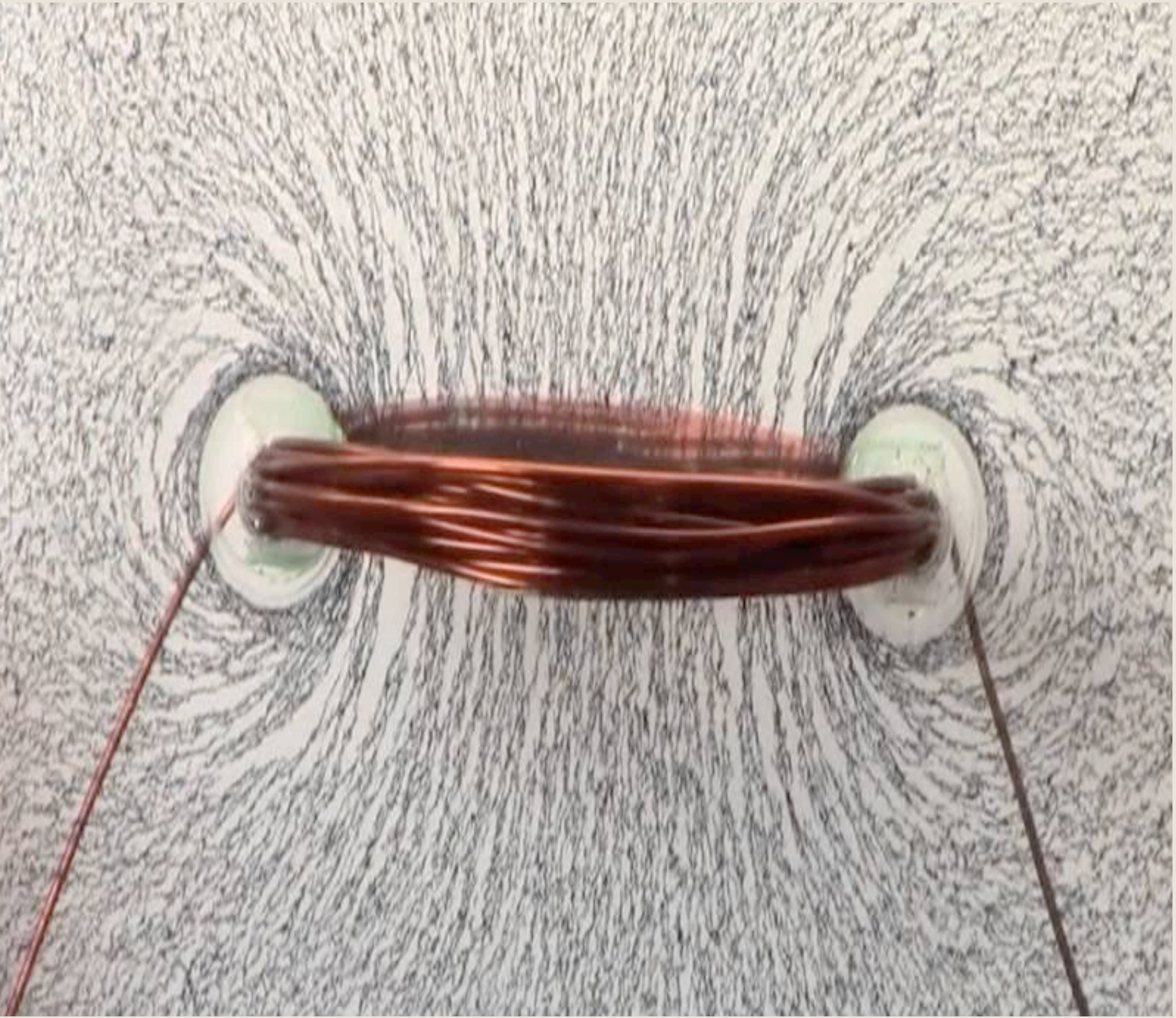
Electric Currents and Magnetism

Long, Straight Wire

- Does a current carrying wire create a magnetic field? YES
- More current, stronger field
- Field strength decreases with distance: note that this is a linear decrease (no inverse square here)
- Right Hand Rule: thumb points current, fingers curl in direction of B field created



Current Loops



- Start with a current-carrying wire
- Field lines are perpendicular to the loop
- Make a coil with multiple loops: Make field even stronger

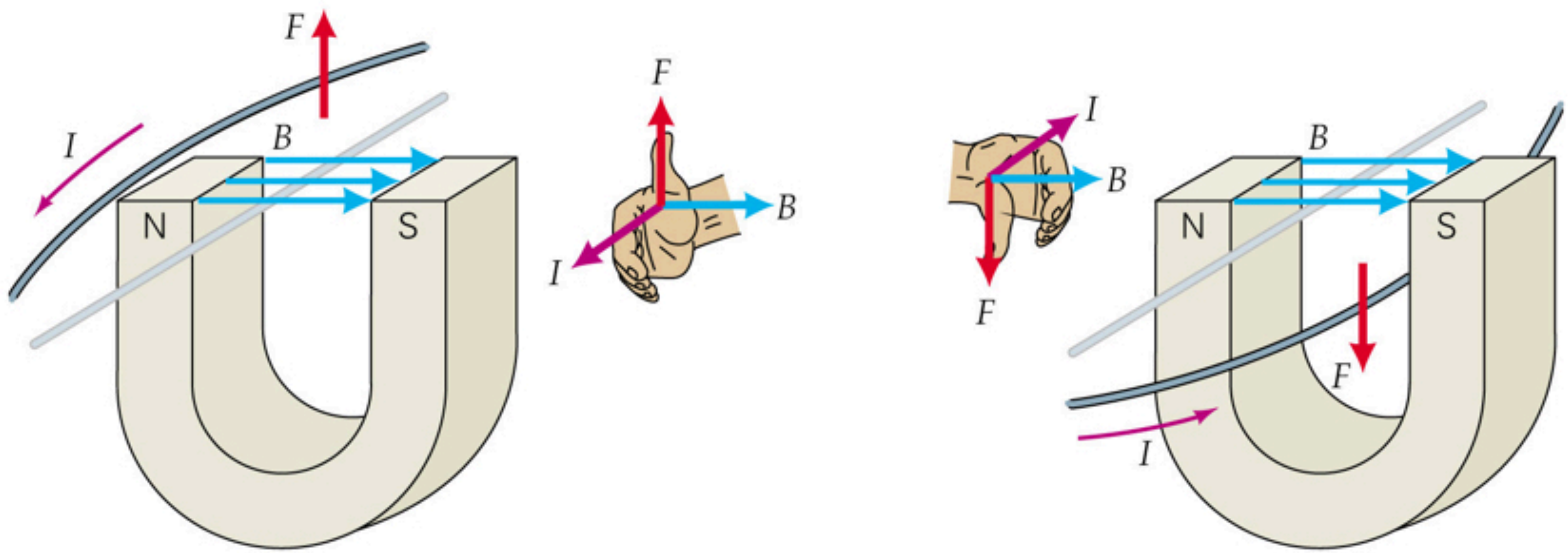
How Do You Make an Electromagnet?

- The name pretty much says it all
- Any current-carrying wire is actually an electromagnet: more current, stronger field
- Wind that coil around an iron core, and you can make an even stronger magnet by inducing the domains in the iron to align

How Strong Can You Make Your Electromagnet?

- Strength is limited by wire: Maximum amount of current (resistance increases with temperature, so wire can carry less current)
- Strength is limited by core: you can only magnetize the iron to the point where all of the domains are aligned; beyond that, more current won't make the iron more magnetic

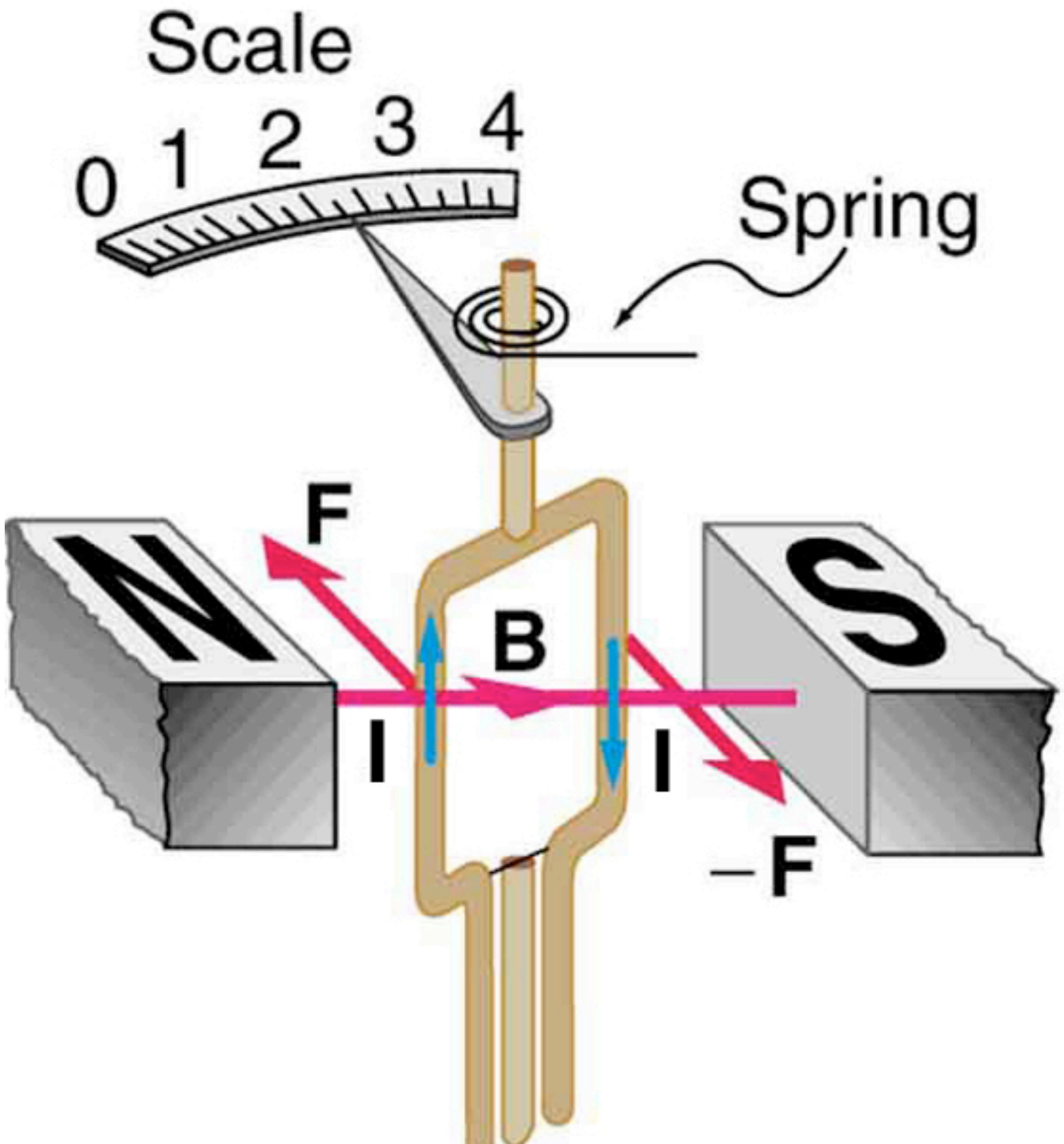
Applications of Electromagnets

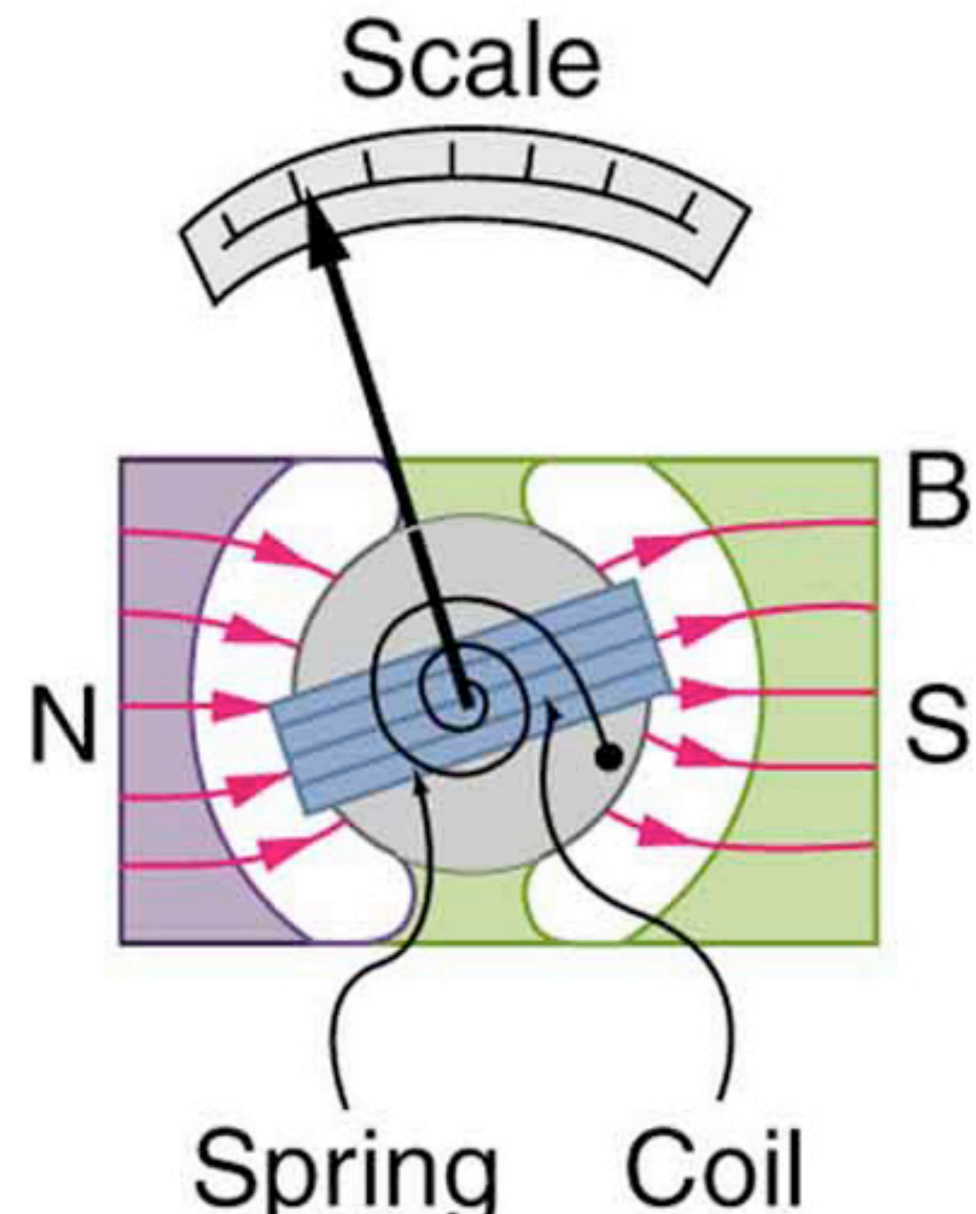


- Magnet pushes current carrying wire: Link to mechanical work!
- If I is perpendicular to B, maximum force
- If I is parallel to B, force = zero

Electric Meters

- Galvanometer uses proportionality: bigger current = bigger push
- Calibrate your dial to measure current, resistance, or voltage! Easy!



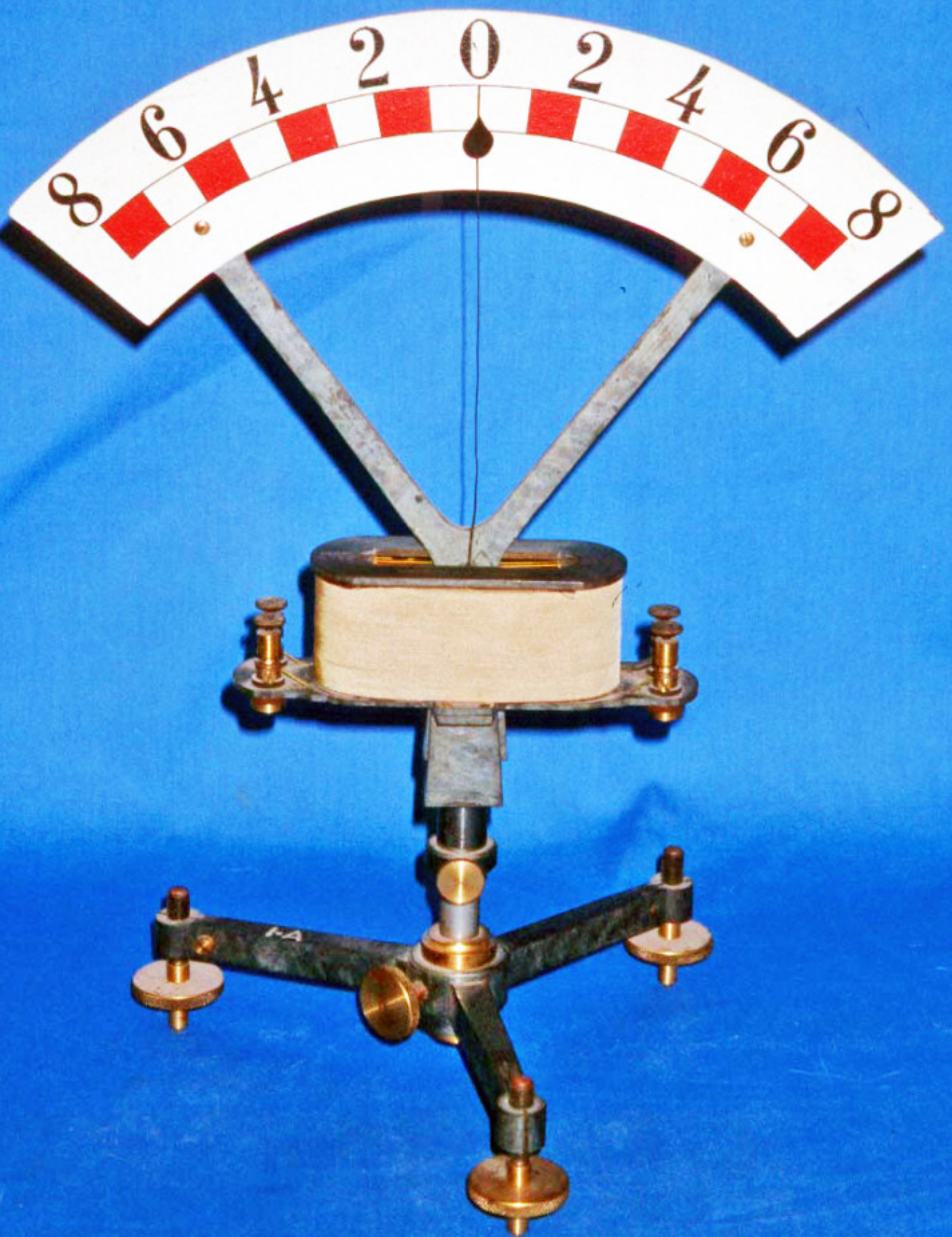


A galvanometer is wired into a simple circuit. When voltage is applied, the needle moves 4 units to the right. Swapping the leads (red-black and black-red) causes the needle to move

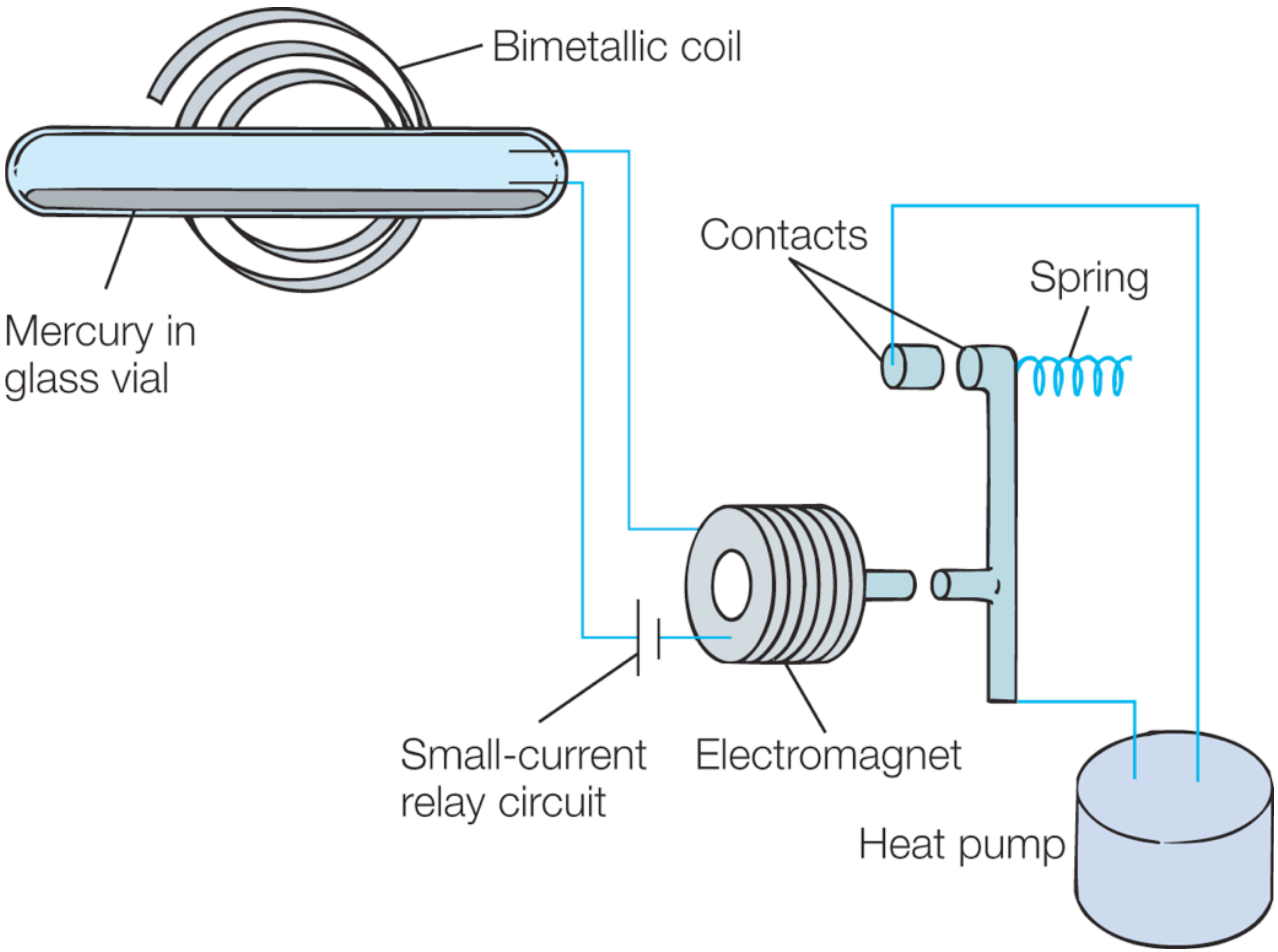
A) 4 units to the right.

B) 4 units to the left.

C) not at all!



Electromagnetic Switches



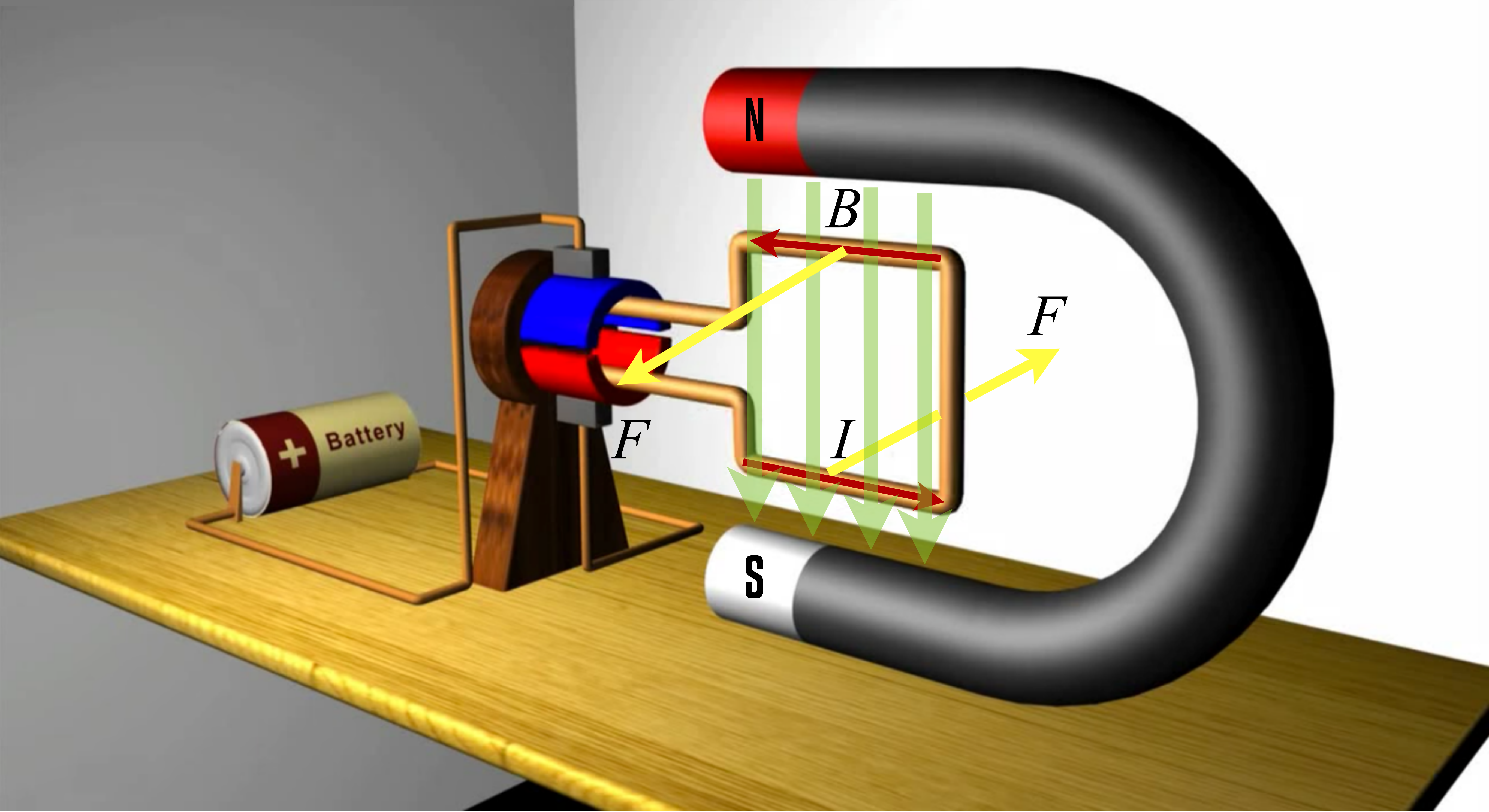
Thermostat! Uses both thermal expansion and electromagnets!

True or false:

This type of relay switch would only work for a thermostat; it could not be applied to other applications.

Electric Motors

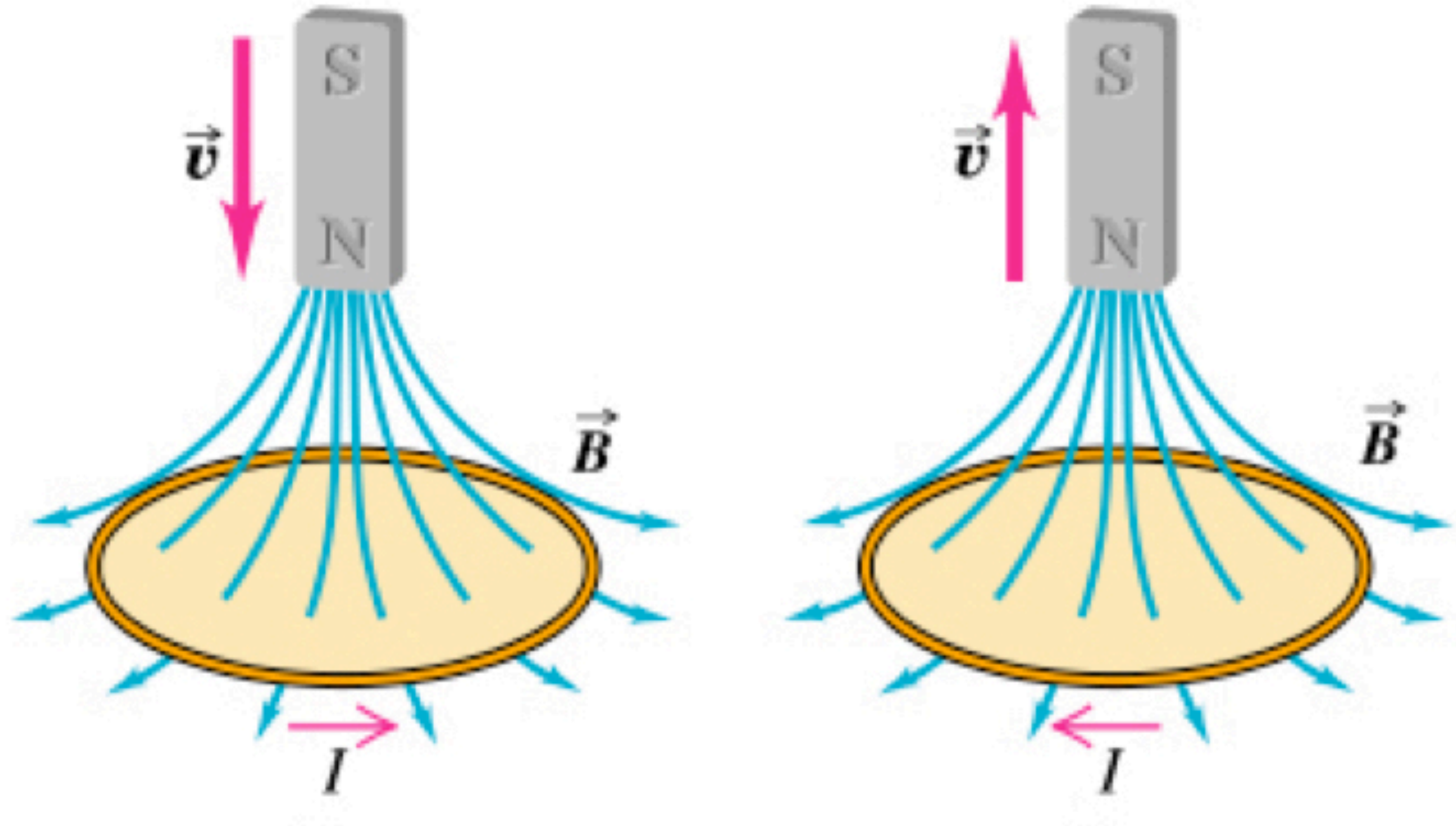
- Energy conversion: Electrical in, mechanical out
- Use electrical input to control magnetic fields to push-pull
- Ceiling fan; blow dryer; stand mixer; blender; coffee grinder; drill; circular saw



Section 6.5

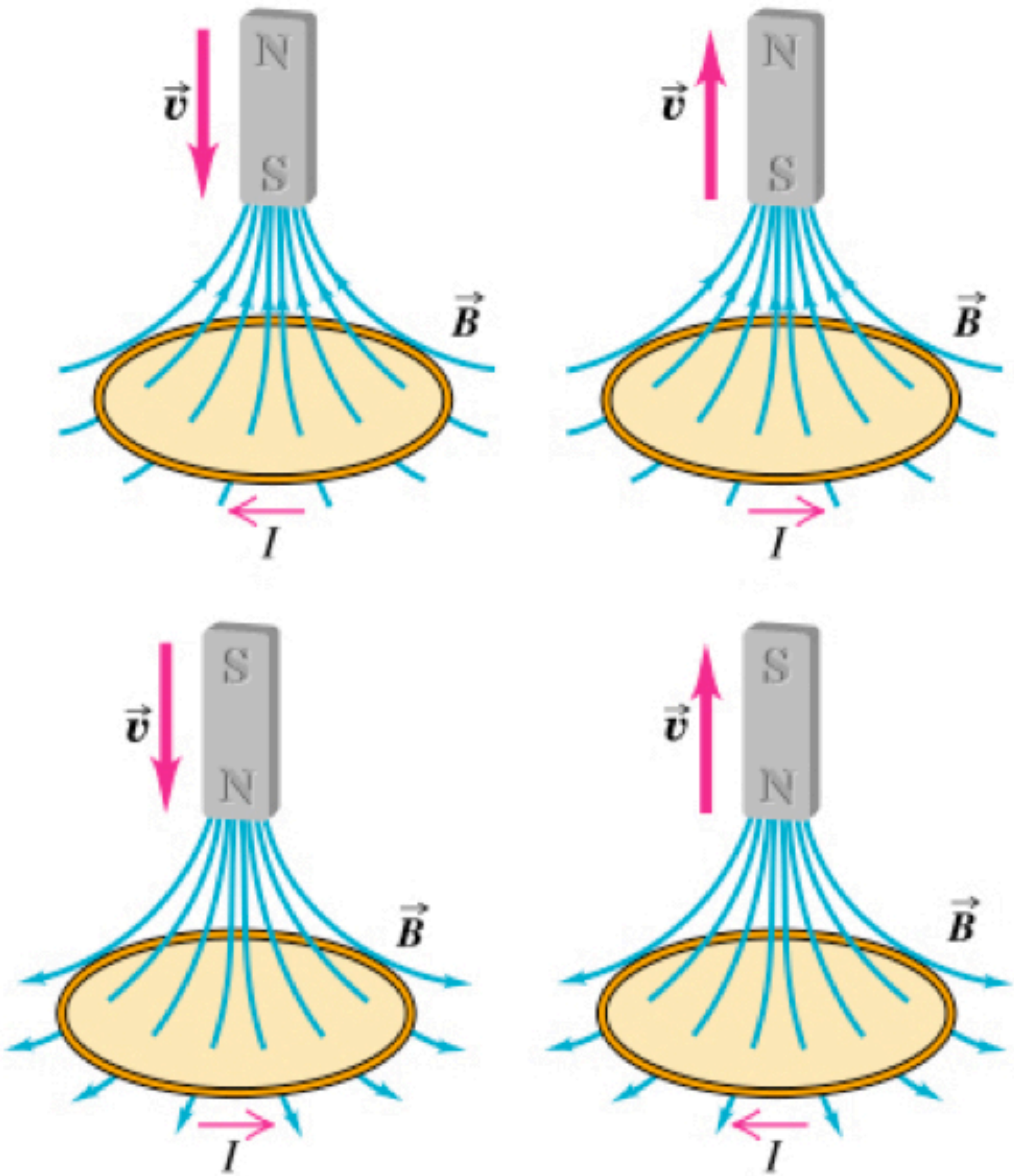
Electro-magnetic Inductions

Faraday and Henry Induce Current



- 1831: Faraday and Henry perform essentially same experiment independently of one another
- Move a permanent magnet through a coil of wire: galvanometer goes bananas!

How Do You Make More Current?



- Stronger magnet
- More loops of wire
- Move the magnet faster
- Move the loop faster

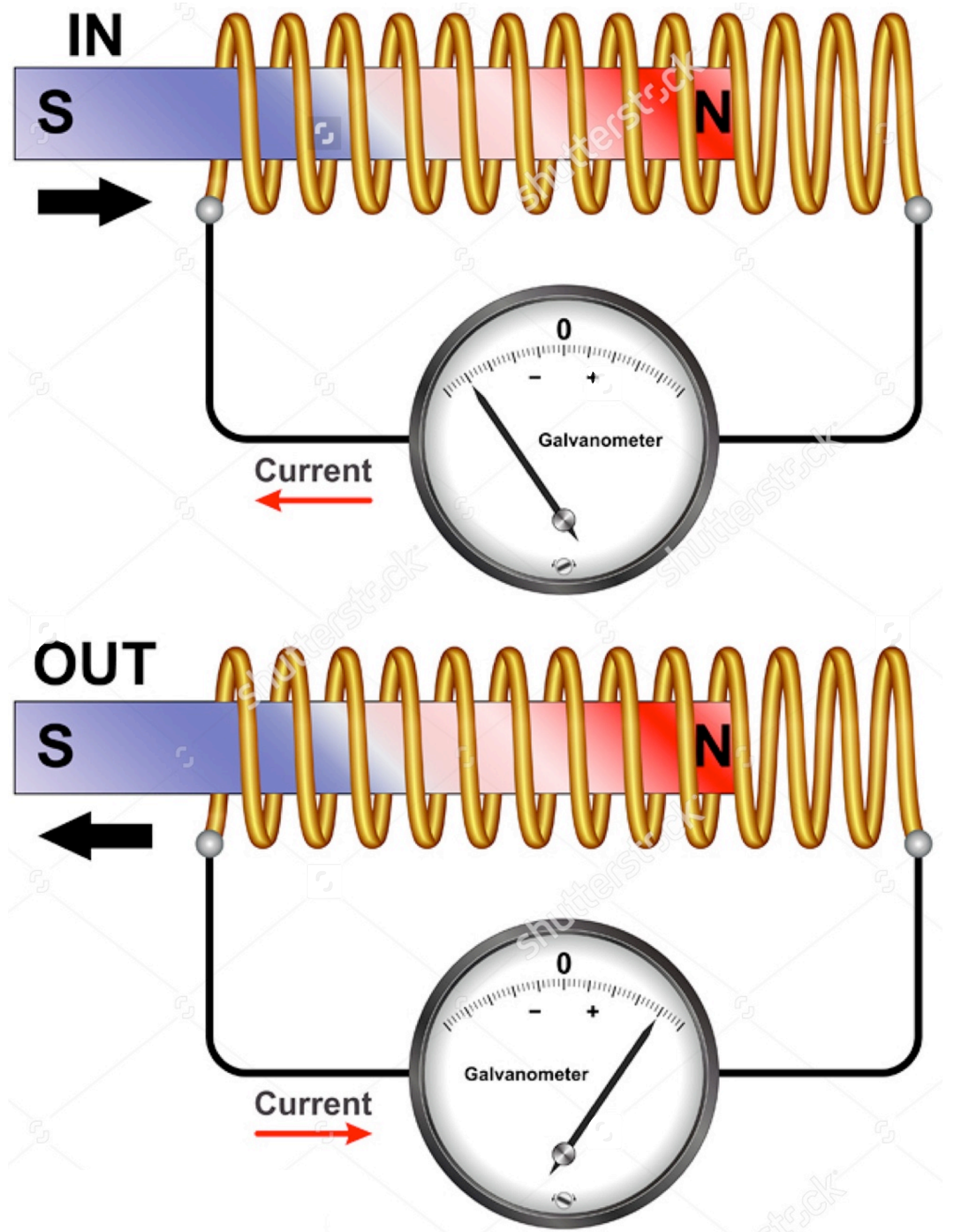
Moving the magnet faster through the loop will

A) induce more current.

B) induce less current.

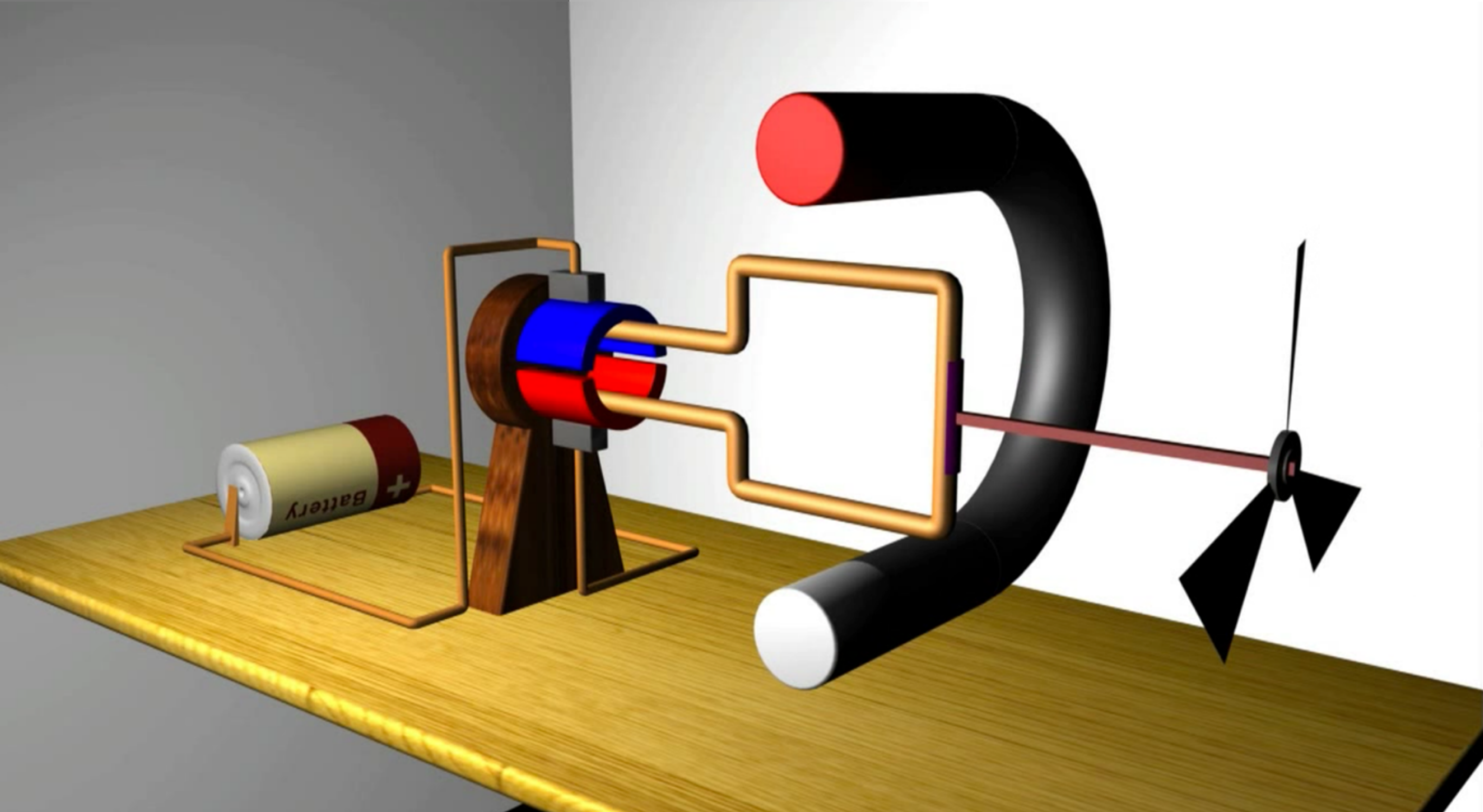
C) induce the same current.

D) induce zero current. Magnets can't make electricity!



Generators

- Precisely the same idea as an electric motor
- Mechanical energy (spin) in, electrical energy (current) out



Transformers

- Two coils wrapped around an iron core
- Primary coil: input alternating current creates time-varying magnetic flux
- Closed iron core loop: concentrates the flux because it's iron–ferromagnetic
- Secondary coil: flux created by primary induces emf in secondary coil

What will the voltmeter read?

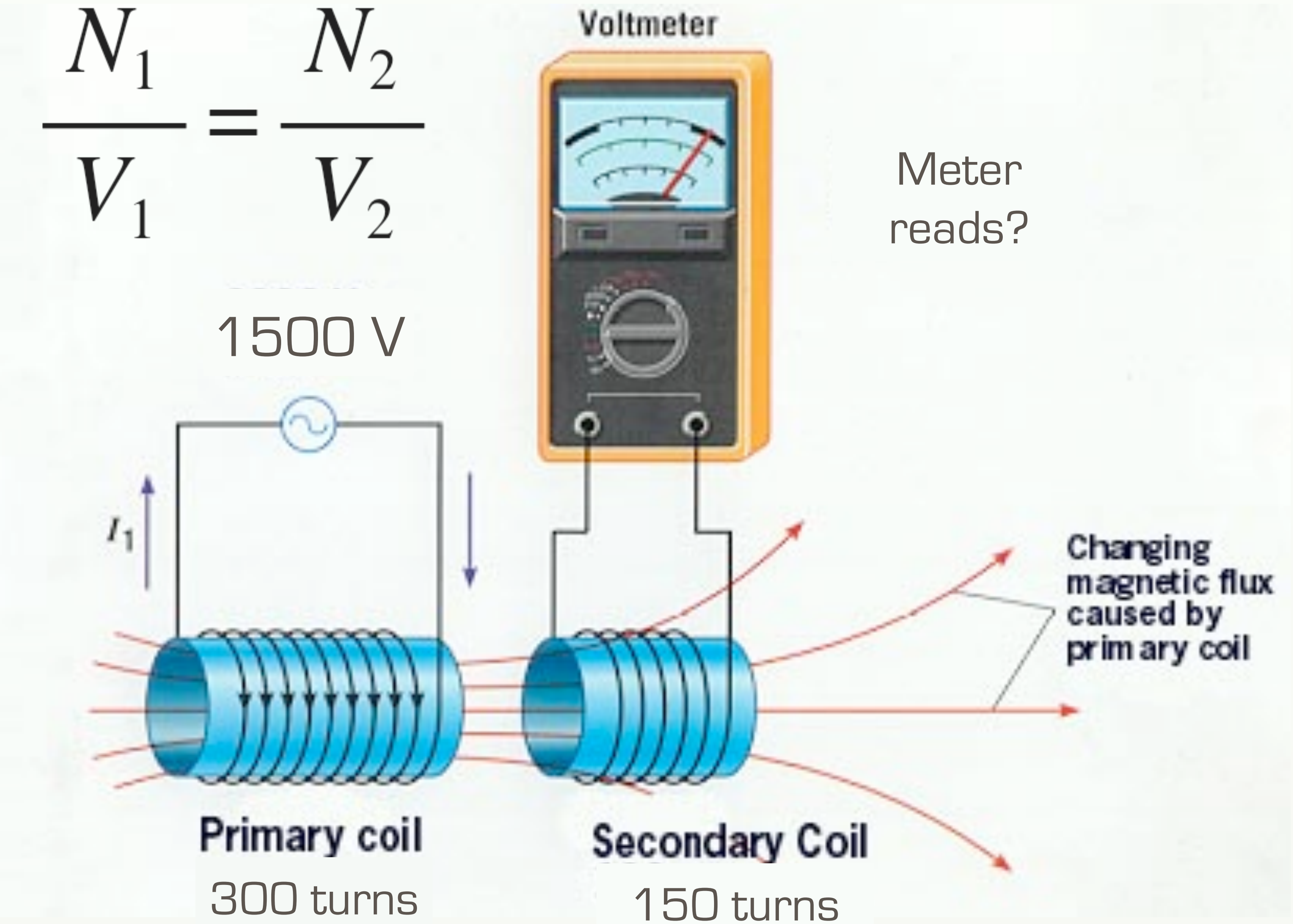
A) 30 V

B) 750 V

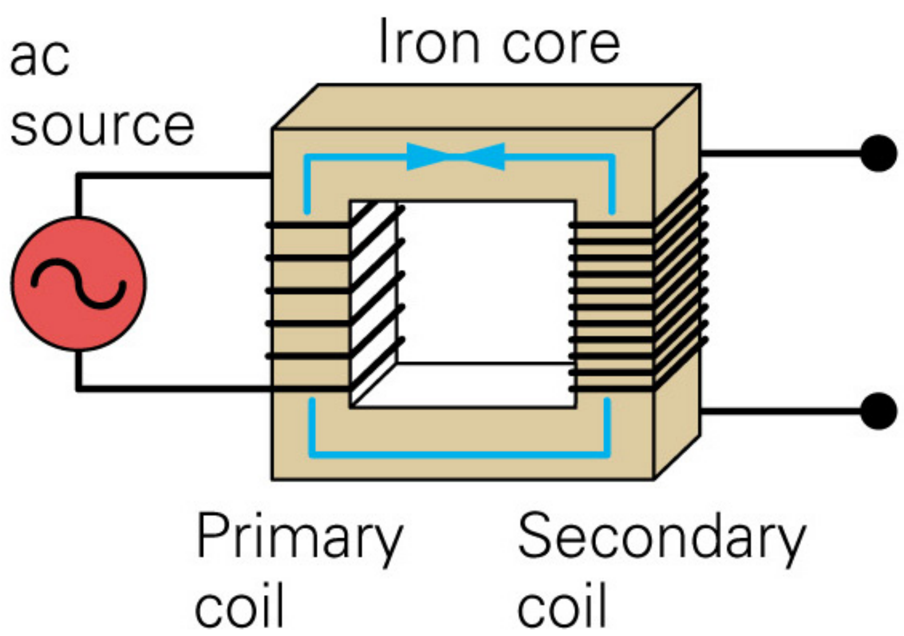
C) 1500 V

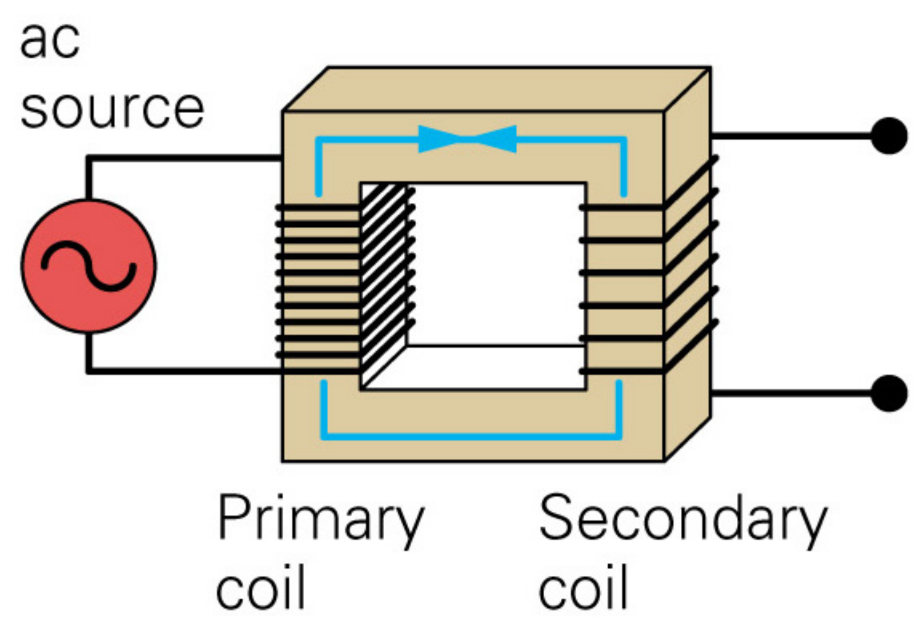
D) 3000 V

$$\frac{N_1}{V_1} = \frac{N_2}{V_2}$$



Step Up or Step Down

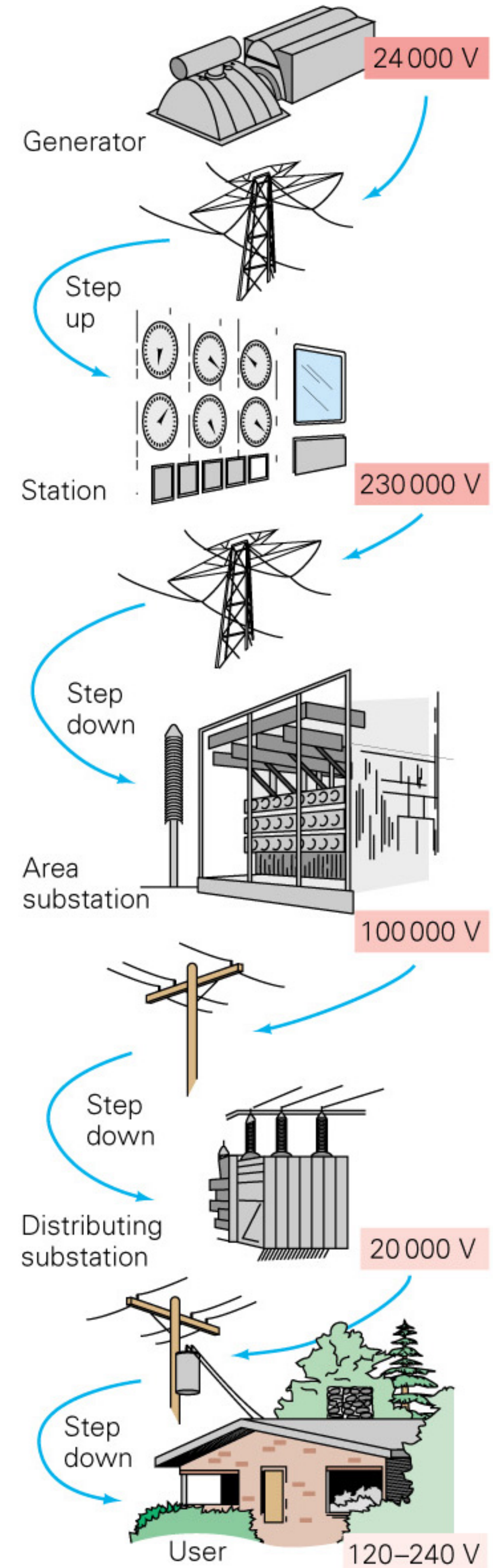


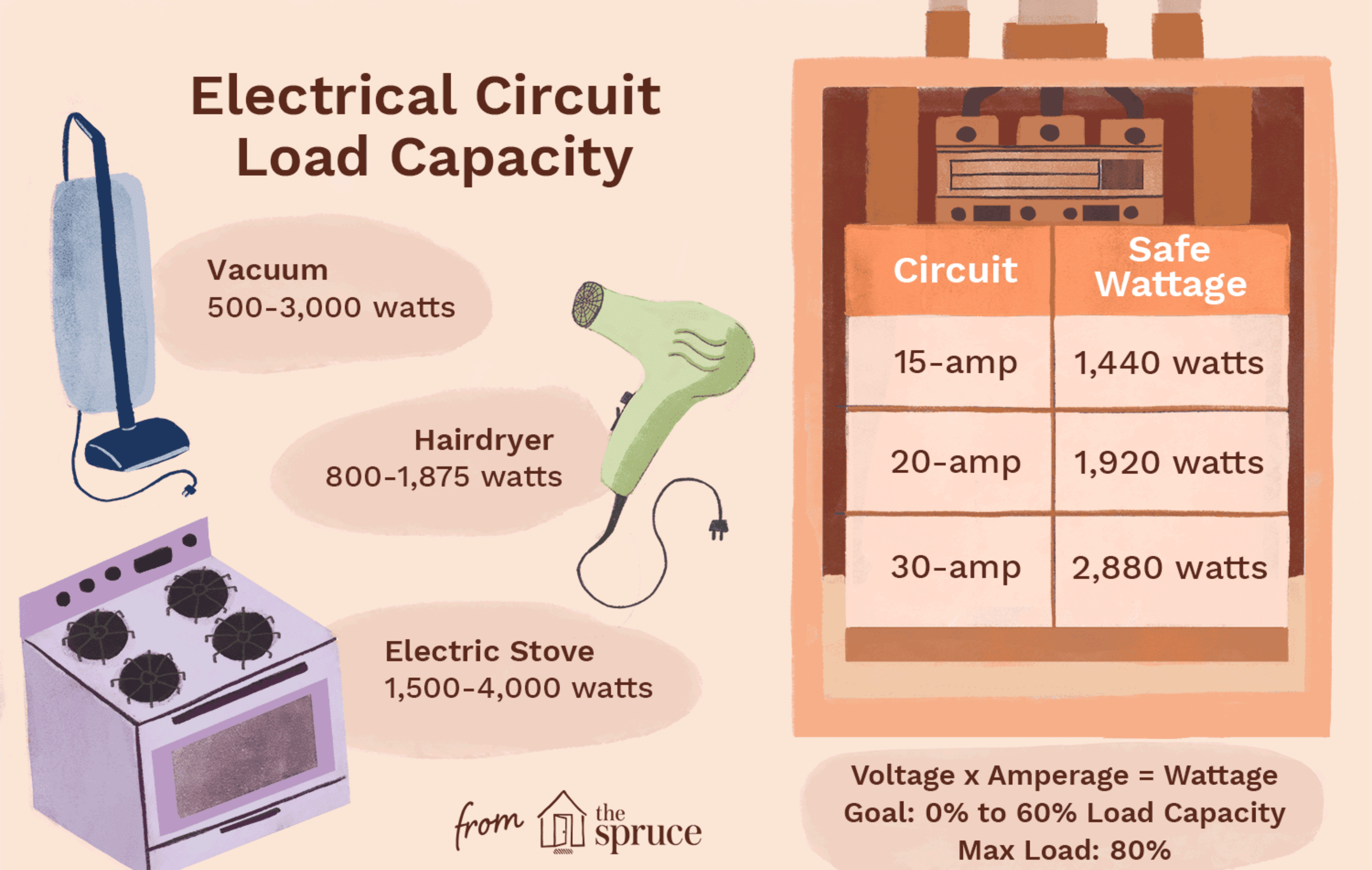


- Step-Up: secondary voltage is higher than primary
  If $V_s > V_p$ then $N_s > N_p$
- Step-Down: secondary voltage is lower than primary
  If $V_s < V_p$ then $N_s < N_p$

Transformers: Why You Need Them

- Transmission over power lines needs to be at very high voltages
- This gives you maximum efficiency with minimum losses
- You household devices are designed to operate with much lower voltages, for obvious reasons
- This is the equivalent of trying to use a soda straw to drink from a firehose
- You need some way to taper that voltage down





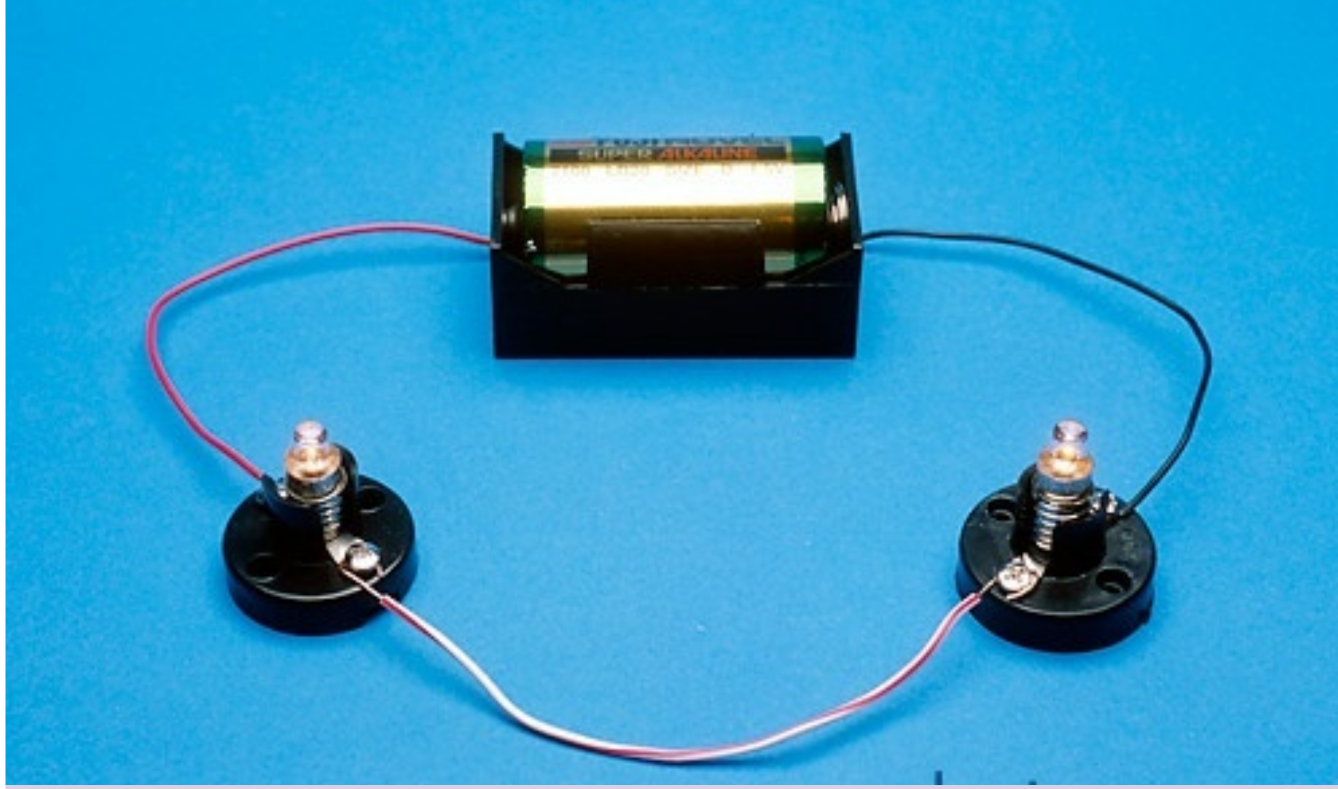
Section 6.6 Circuit Connections

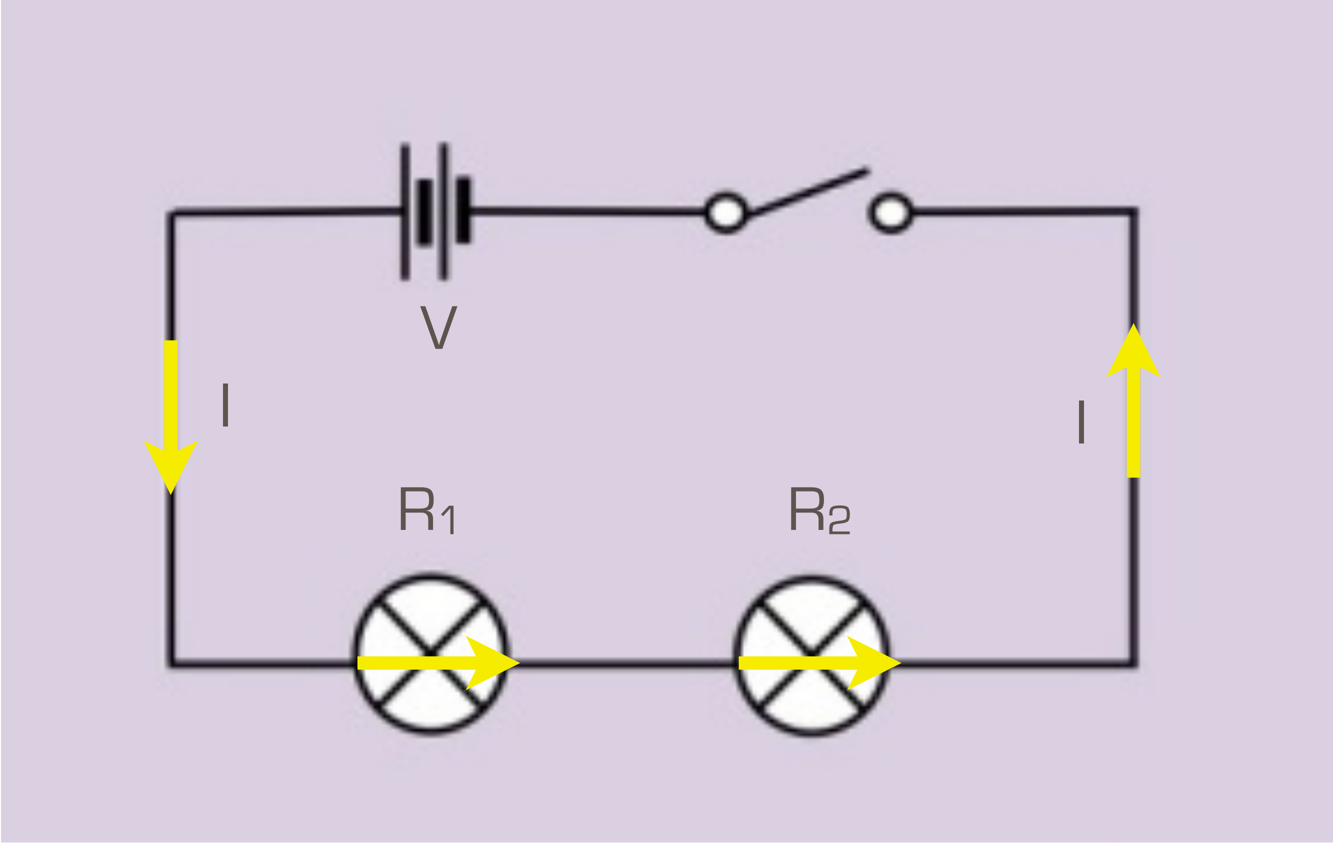
Voltage Sources In Circuits

- AC: Alternating current drives devices that you plug in to the wall
- DC: Direct current drives battery-operated devices
- Yes, I know some of these are not electrical devices at all!

Series Circuit

- Devices are added along the same path: there is one and only one path for electrons to follow
- Every electron must pass through every device in the circuit: cut one device, entire circuit goes out
- Same current through every device (current is common)
- Different voltage across each resistor: depends on resistance of device (use Ohm's law)
- Add more devices, makes it harder for the electrons to get around the circuit: more devices, more resistance





$$V = I(R_1 + R_2 + \ldots + R_n)$$

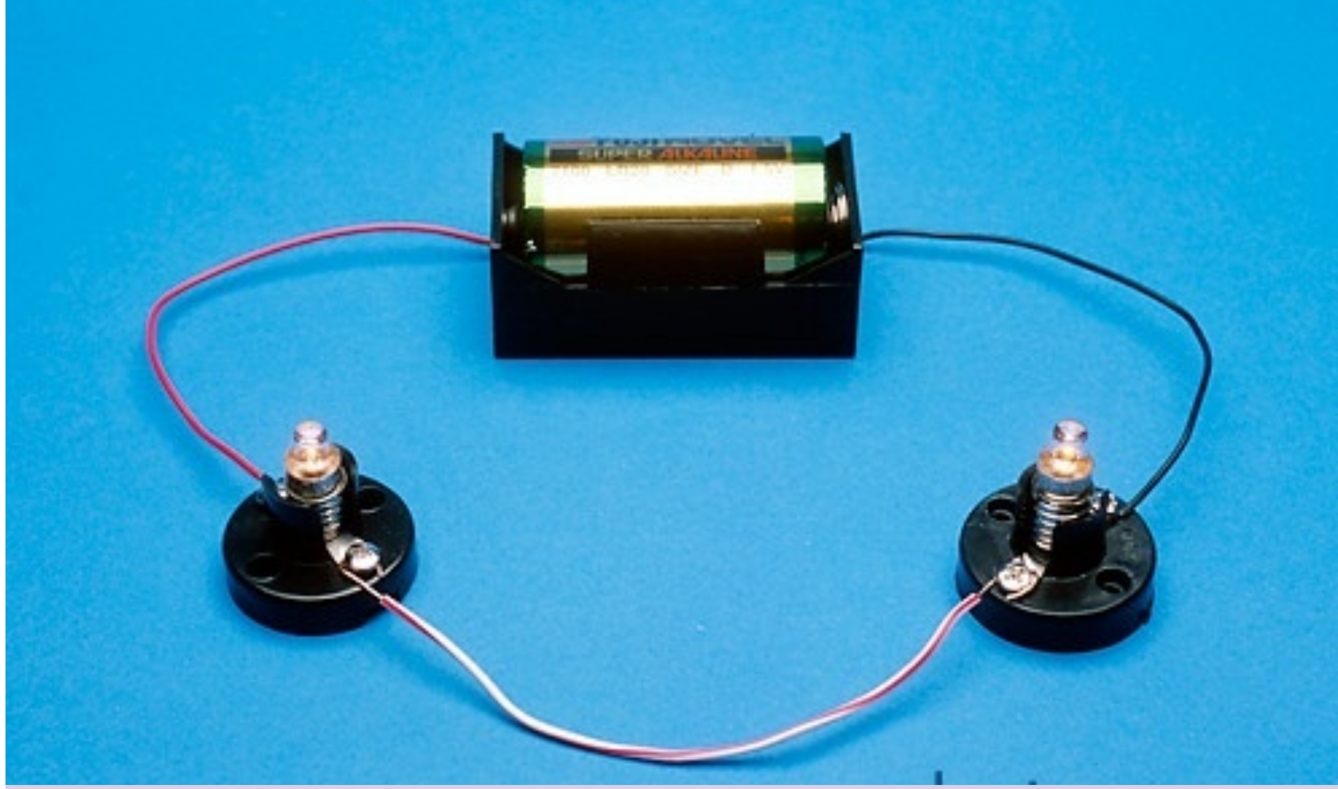
$$V = V_1 + V_2 + \ldots + V_n$$

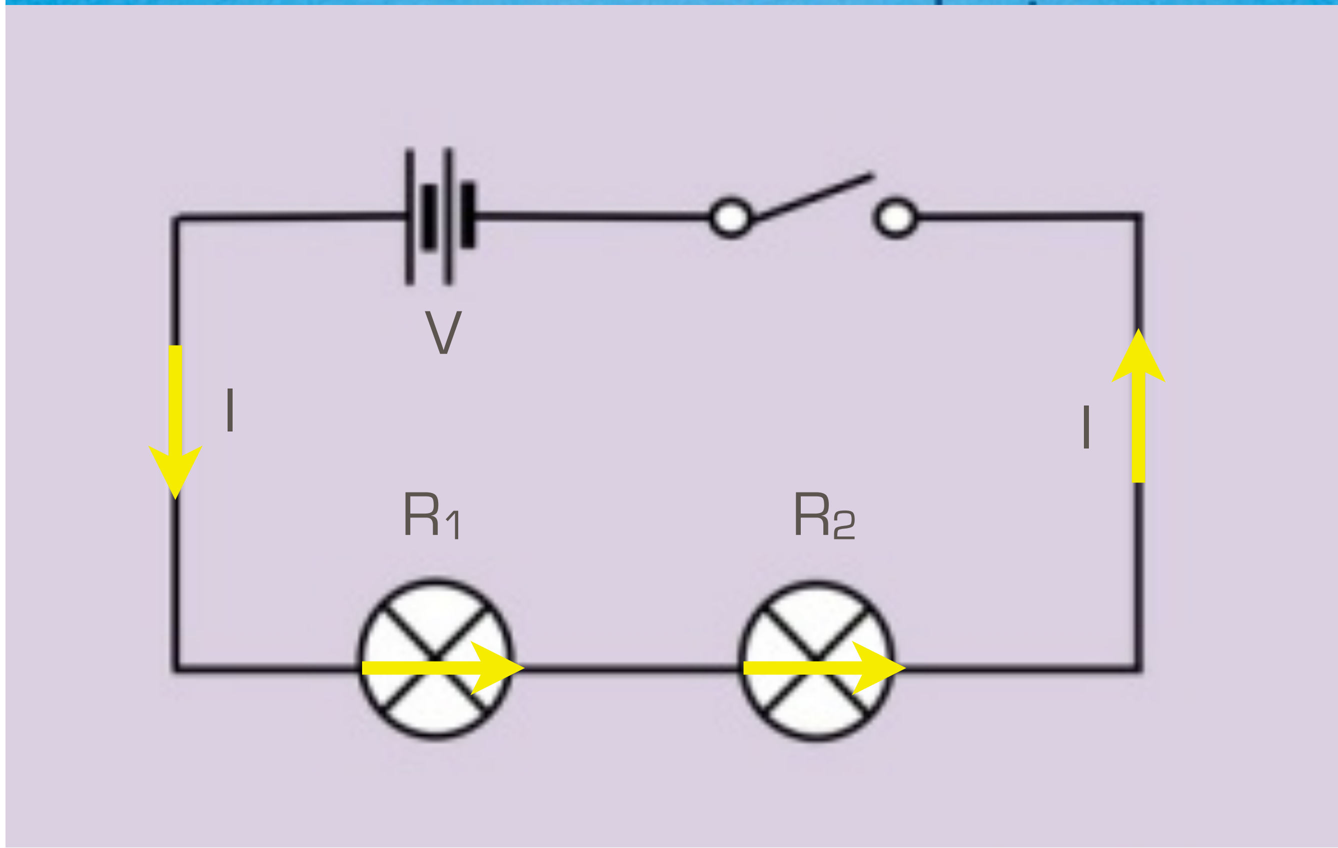
Series Example

Using a 12-V battery, wire two 3Ω bulbs in series:

$$V = 12\text{V}$$
$$R_1 = 3\Omega$$
$$R_2 = 3\Omega$$

$$R = R_1 + R_2$$
$$R = 3\Omega + 3\Omega = 6\Omega$$
$$V = IR$$
$$12\text{V} = I(6\Omega)$$
$$I = \frac{12\text{V}}{6\Omega} = 2\text{A}$$
$$V_1 = IR_1 = (2\text{A})(3\Omega) = 6\text{V}$$
$$V_2 = IR_2 = (2\text{A})(3\Omega) = 6\text{V}$$
$$V = V_1 + V_2 = 6\text{V} + 6\text{V} = 12\text{V}$$





$$V = I(R_1 + R_2 + \ldots + R_n)$$
$$V = V_1 + V_2 + \ldots + V_n$$

Calculate the total (equivalent) resistance.

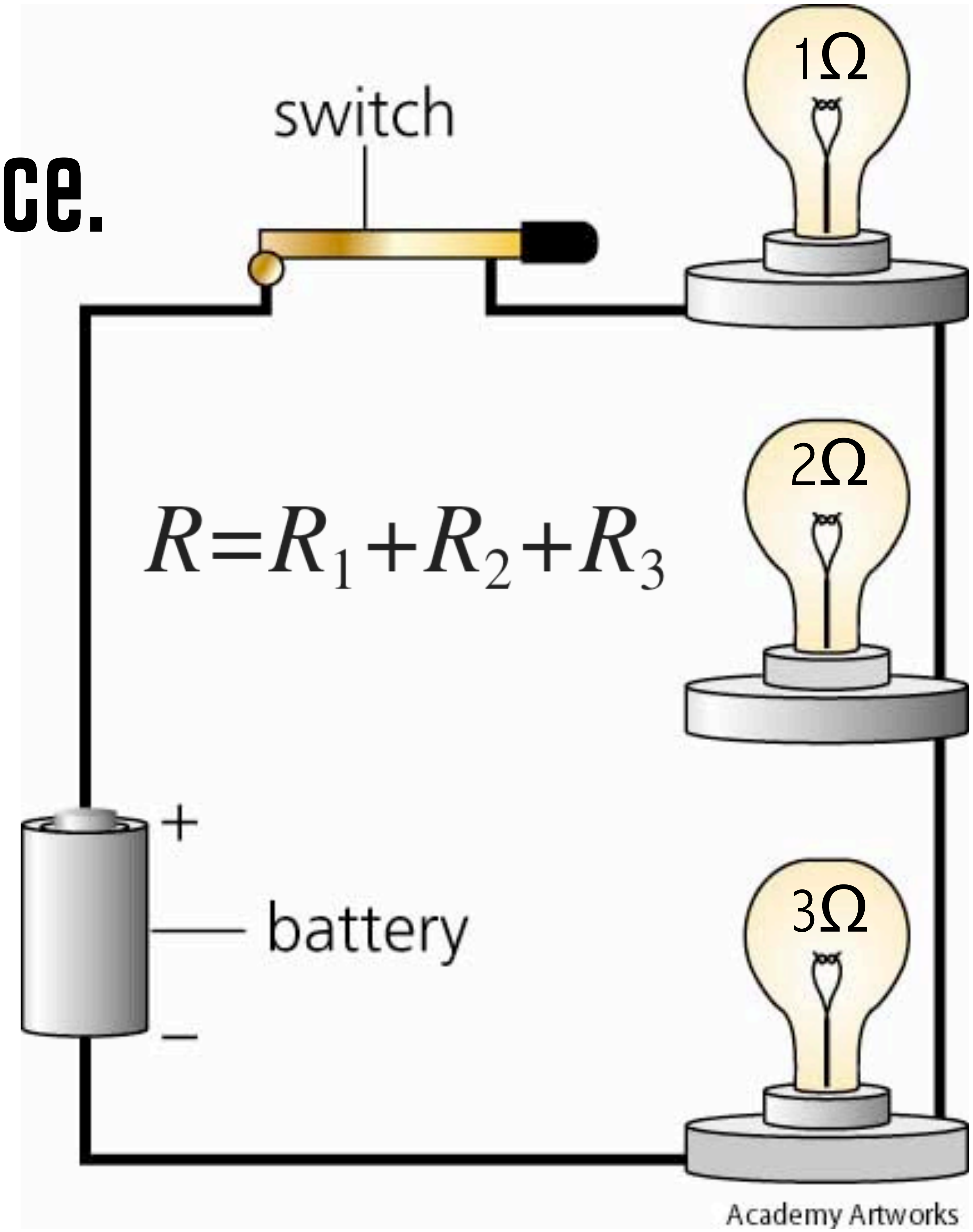
A) 0Ω

B) 2Ω

C) 4Ω

D) 6Ω

E) 12Ω



Calculate the voltage across each bulb.

$$R = R_1 + R_2 + R_3 = ?$$

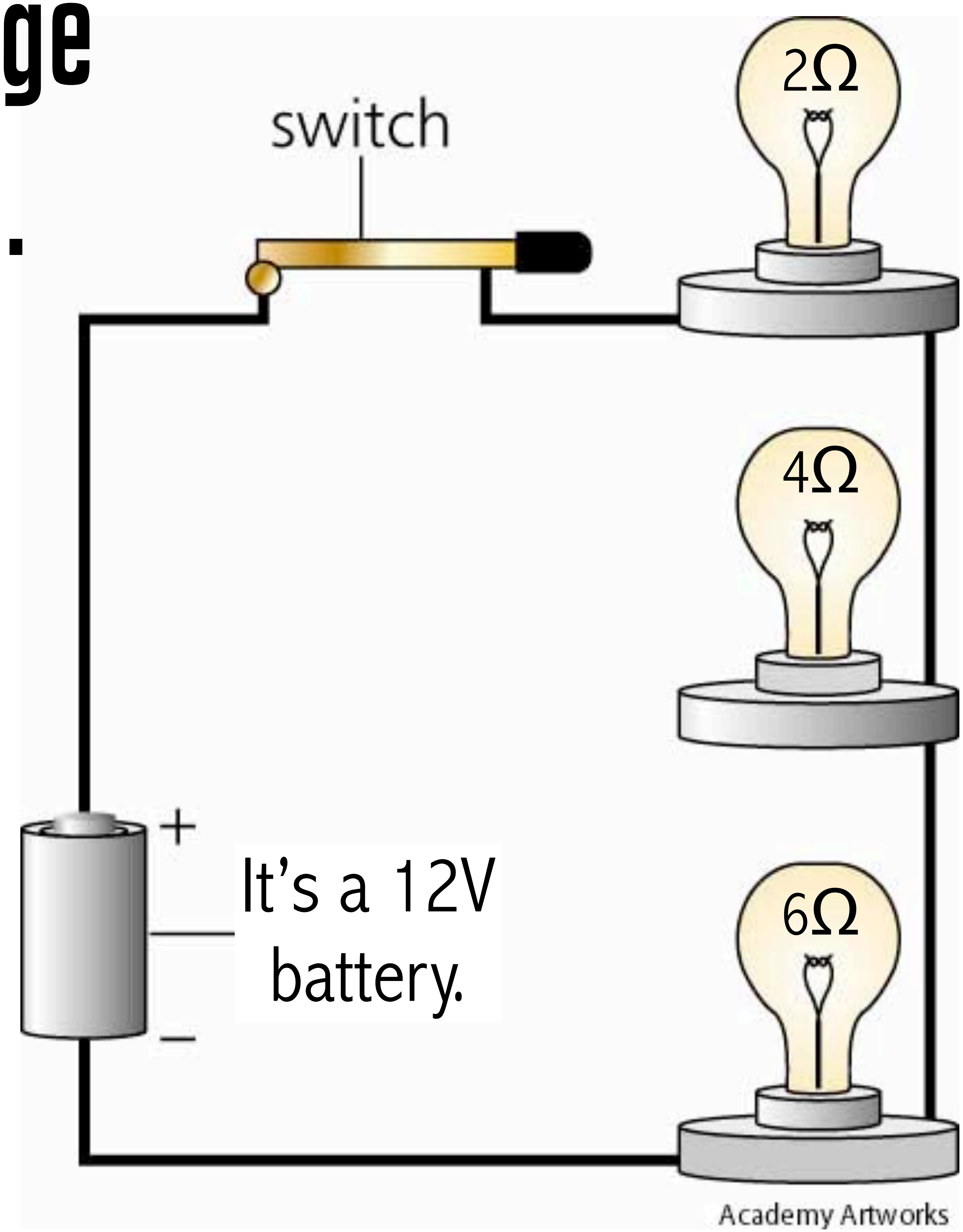
$$V = IR \Rightarrow I = \frac{V}{R}$$

$$I = \frac{12\text{V}}{(R_1 + R_2 + R_3)} = ?$$

$$V_1 = IR_1 = I(2\Omega) = ?$$

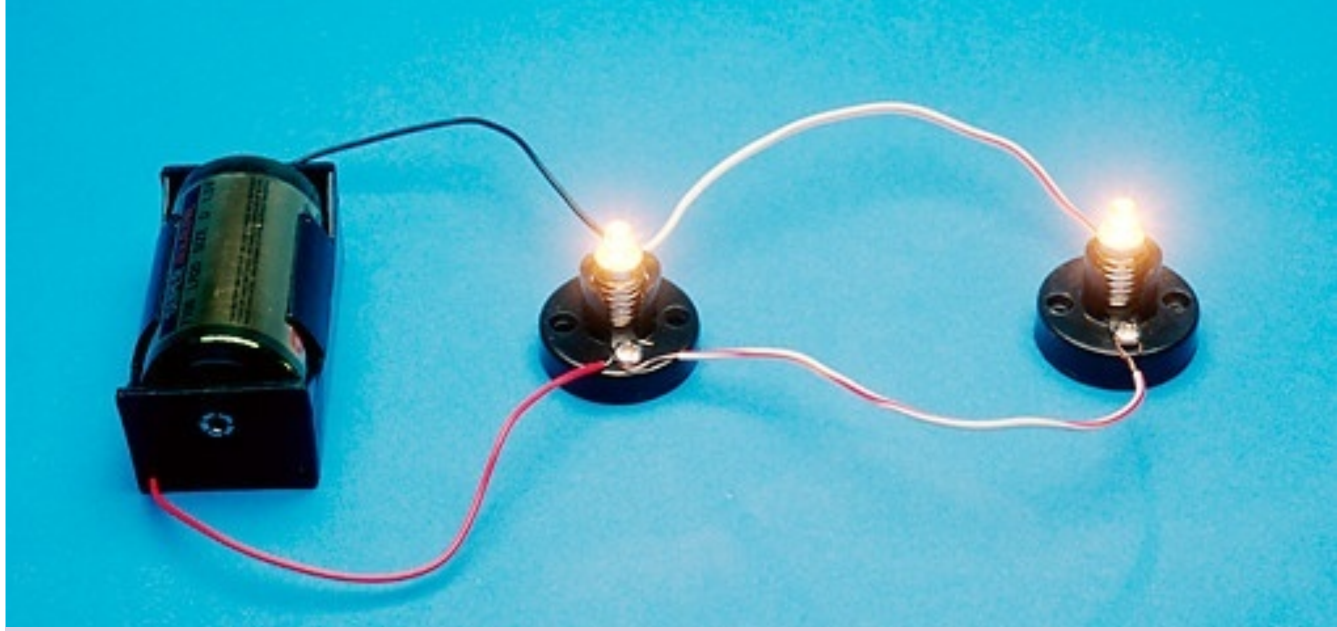
$$V_2 = IR_2 = I(4\Omega) = ?$$

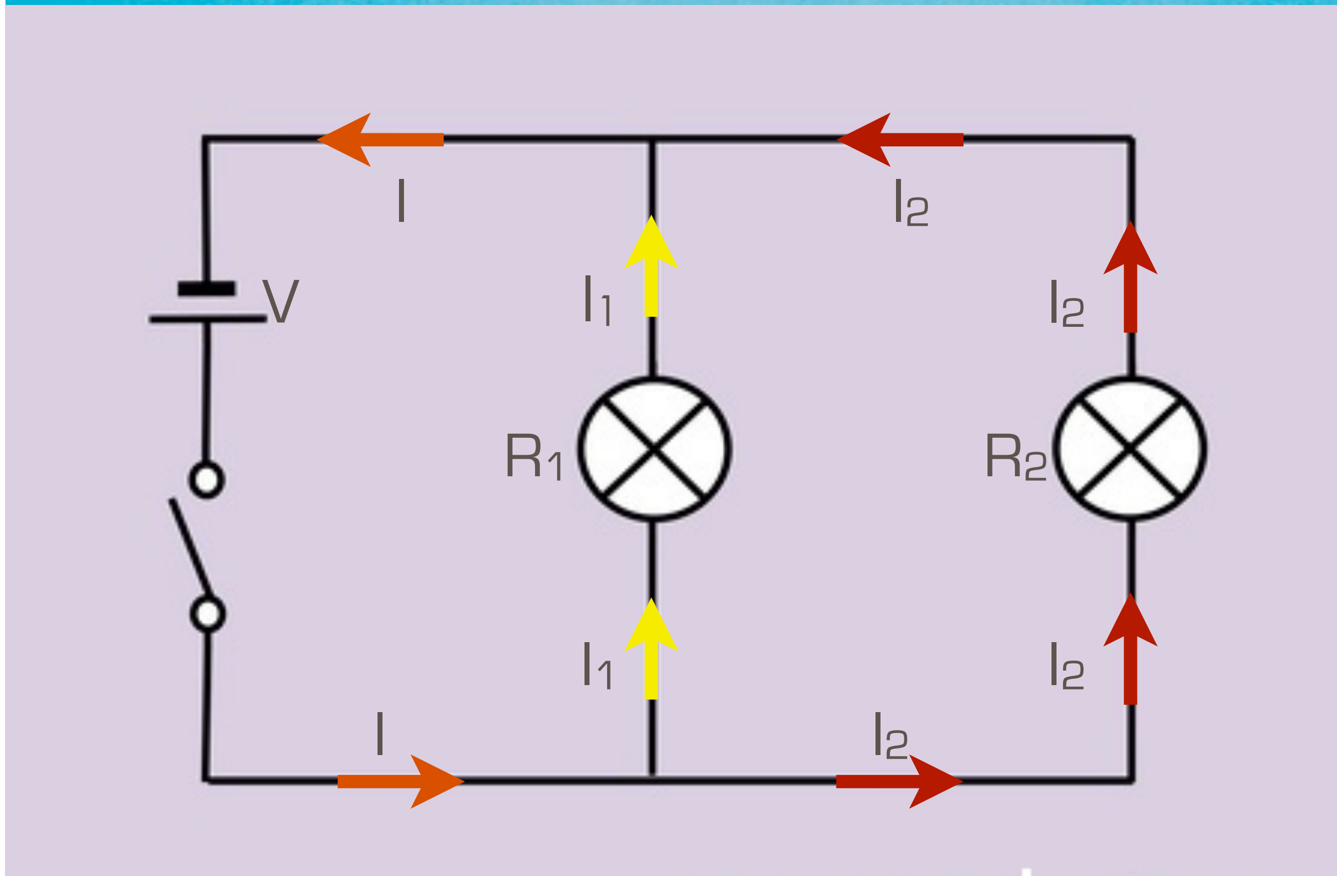
$$V_3 = IR_3 = I(6\Omega) = ?$$



Parallel Circuit

- Each device is added to the circuit on its own path: many possible paths for electrons to follow
- Each path is independent of the other pathways: cut one device, others are unaffected
- Any electron cannot pass through every device: can only travel one pathway
- Same voltage across every device (voltage is common): every path starts and ends at same points
- Different current through each path: amount of current depends on resistance of device (use Ohm's Law)
- Add more devices, opens more pathways: can pull more electrons through the circuit–more devices, less resistance





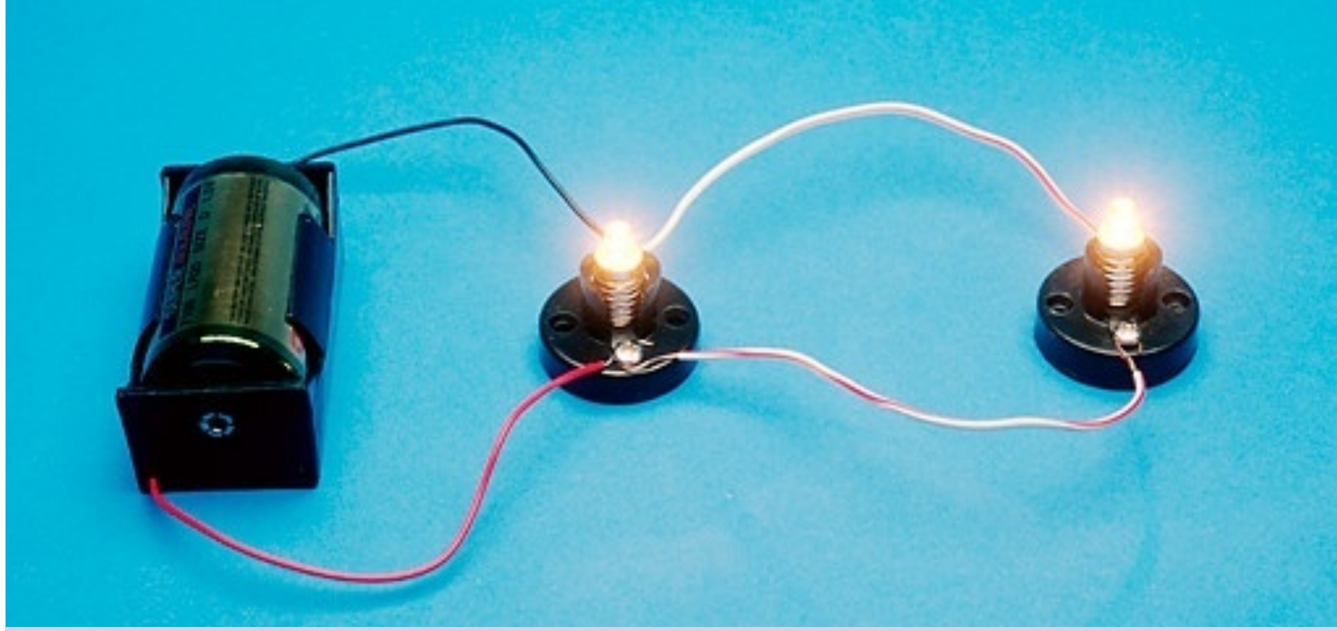
$$I = I_1 + I_2 + \ldots + I_n$$

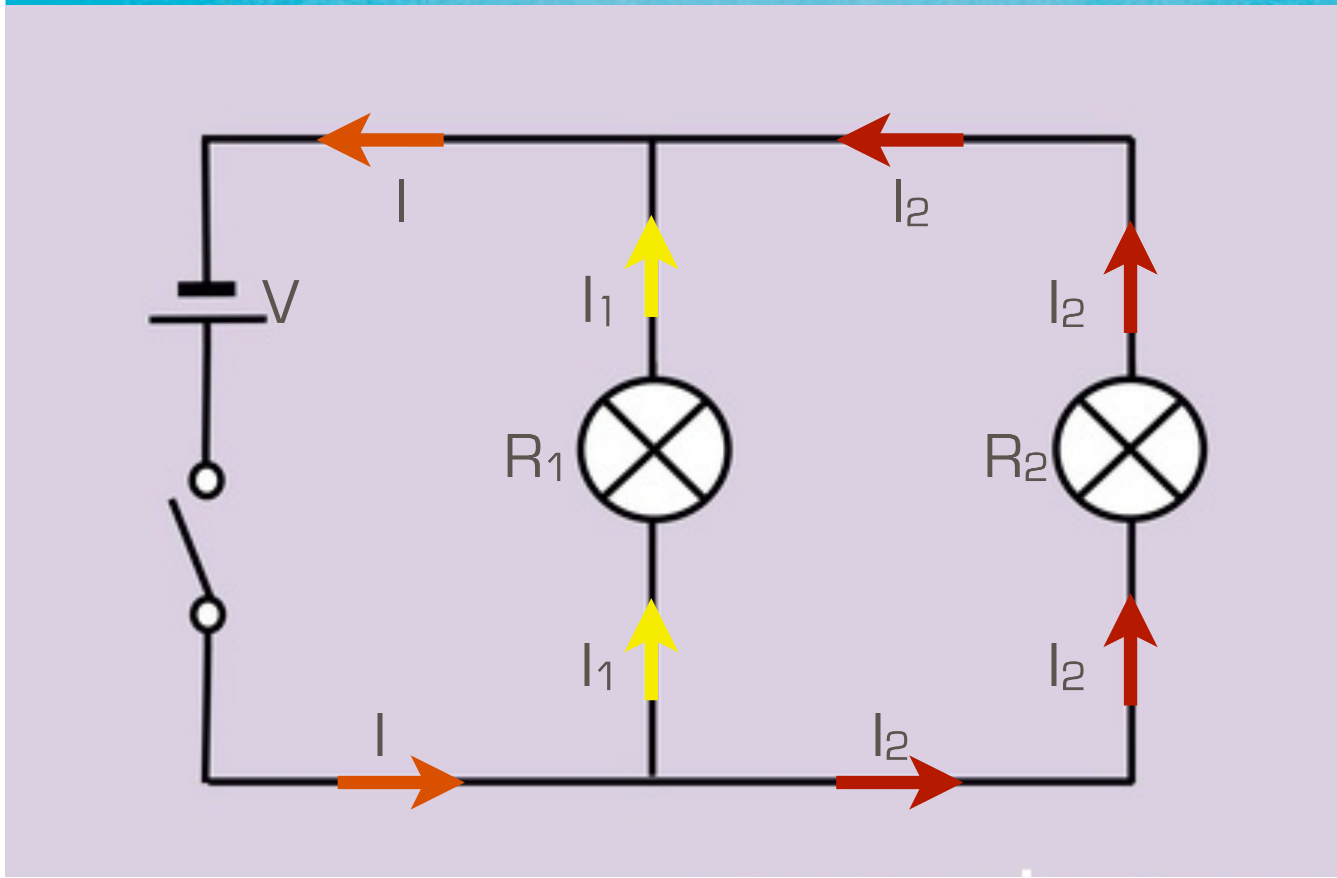
$$I = V/R_1 + V/R_2 + \ldots + V/R_n$$

Parallel Example

Using a 12-V battery, wire two 3Ω bulbs in parallel:

$$V=12\text{V}$$
$$R_1=3\Omega$$
$$R_2=3\Omega$$





$$V_1=V=12\text{V} \qquad V_2=V=12\text{V}$$

$$V=IR \Rightarrow I=\frac{V}{R}$$

$$I_1=\frac{V_1}{R_1}=\frac{12\text{V}}{3\Omega}=4\text{A}$$

$$I_2=\frac{V_2}{R_2}=\frac{12\text{V}}{3\Omega}=4\text{A}$$

$$I=I_1+I_2=4\text{A}+4\text{A}=8\text{A}$$

$$I = I_1 + I_2 + \ldots + I_n$$

$$I = V/R_1+V/R_2+\ldots+V/R_n$$

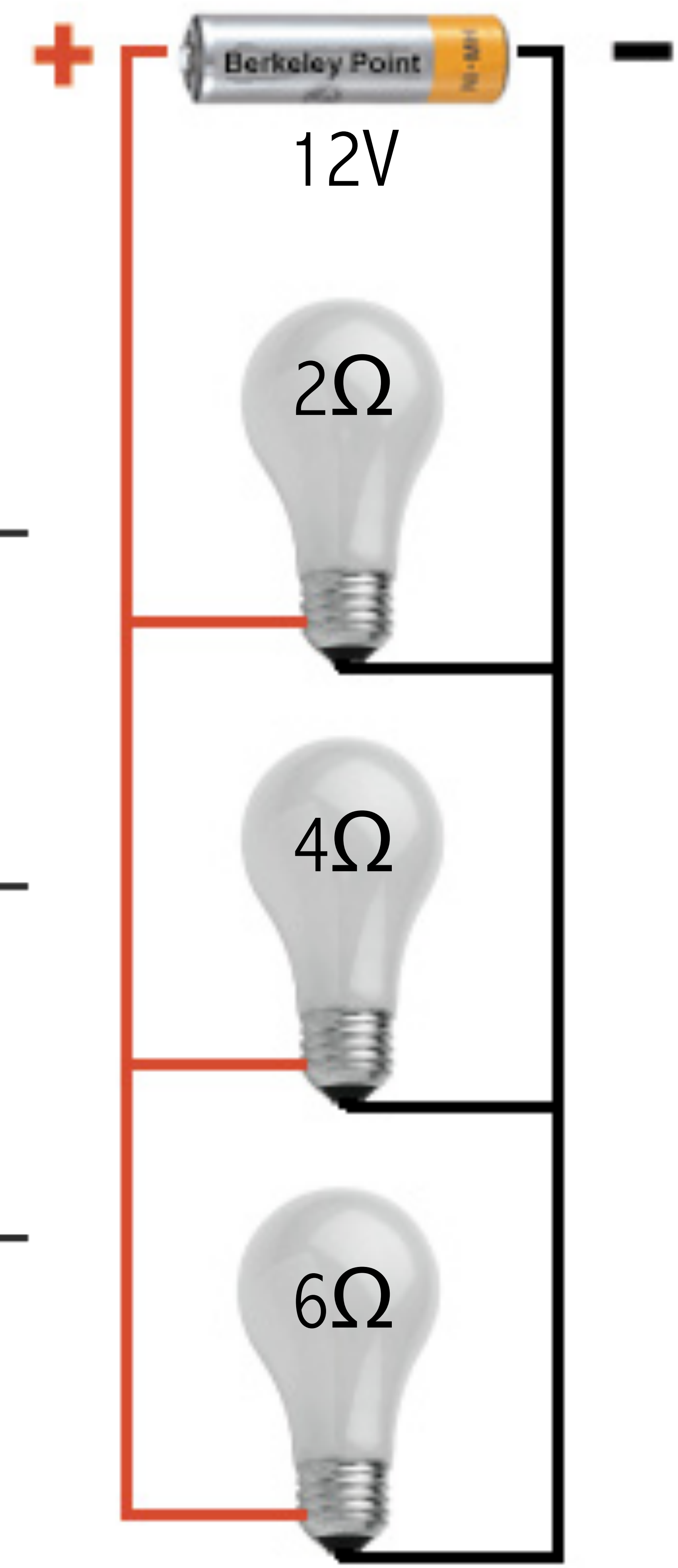
Calculate the total current.

- The voltage across each bulb is the same: $V_1 = V_2 = V_3 = V = 12V$
- Calculate the current through each bulb
- Add them up! $I = I_1 + I_2 + I_3$

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

$$I_3 = \frac{V}{R_3}$$



A) 1A

B) 11A

C) 12A

D) 144A

Household Circuits

- Series or parallel? What makes sense here?
- Multiple separate parallel circuits, protected by fuses/ circuit breakers
- Old-timey fuses: Tin strip melts if it gets too hot, breaking the circuit
- Modern breakers: See thermostat above! Exactly the same kind of switch!