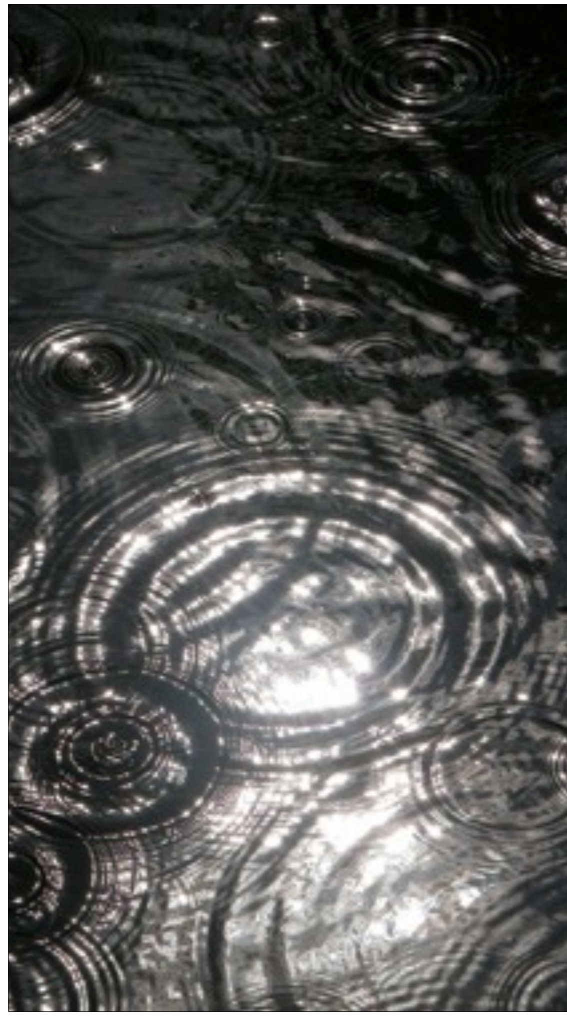
The Nature of Gravity, Electricity, & Magnetism

ACT III: FIELDS — FORCES AT A DISTANCE



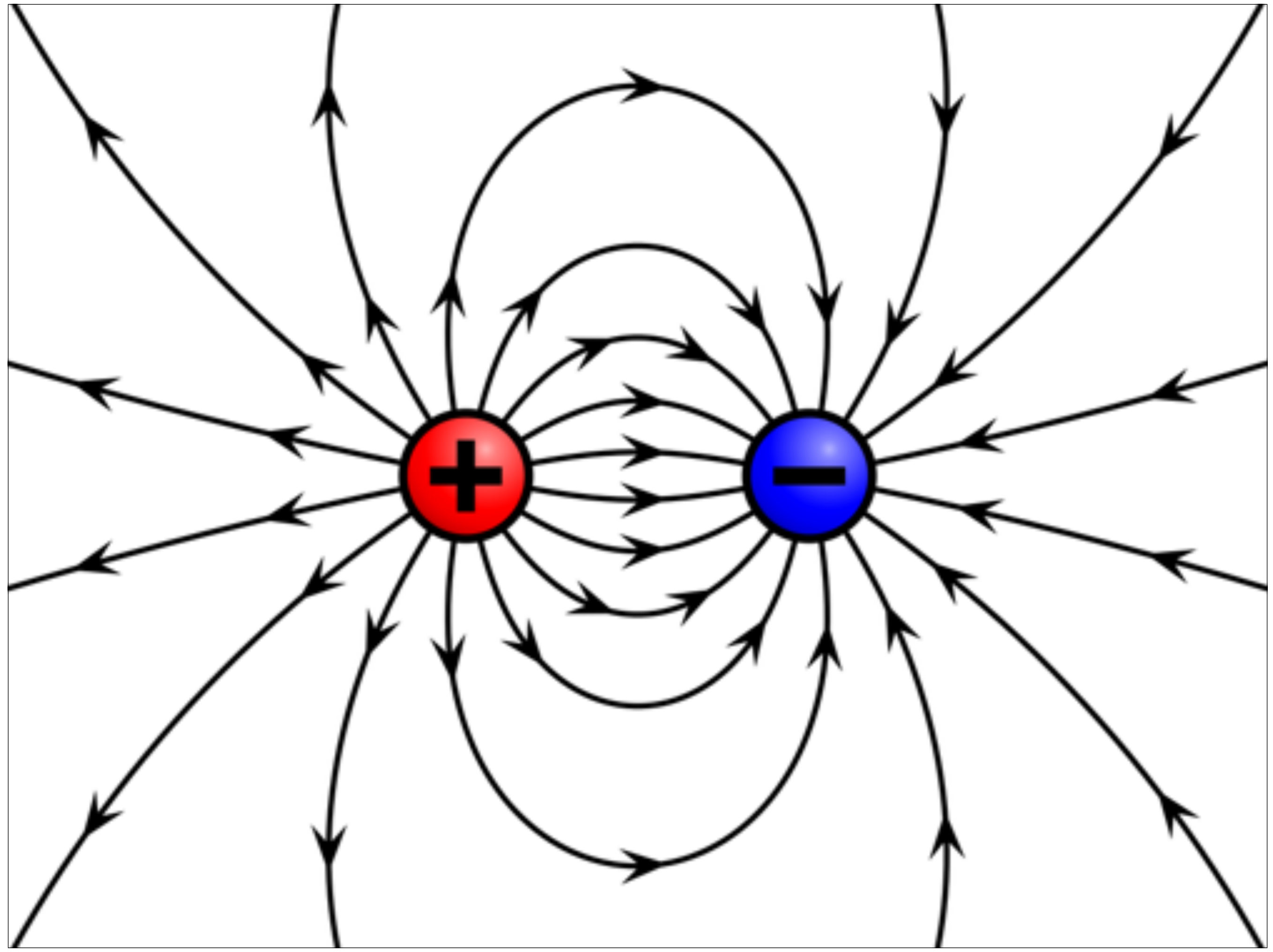
What are force fields – how do they work – why are they useful?

SCENE I: THINKING IN FIELDS

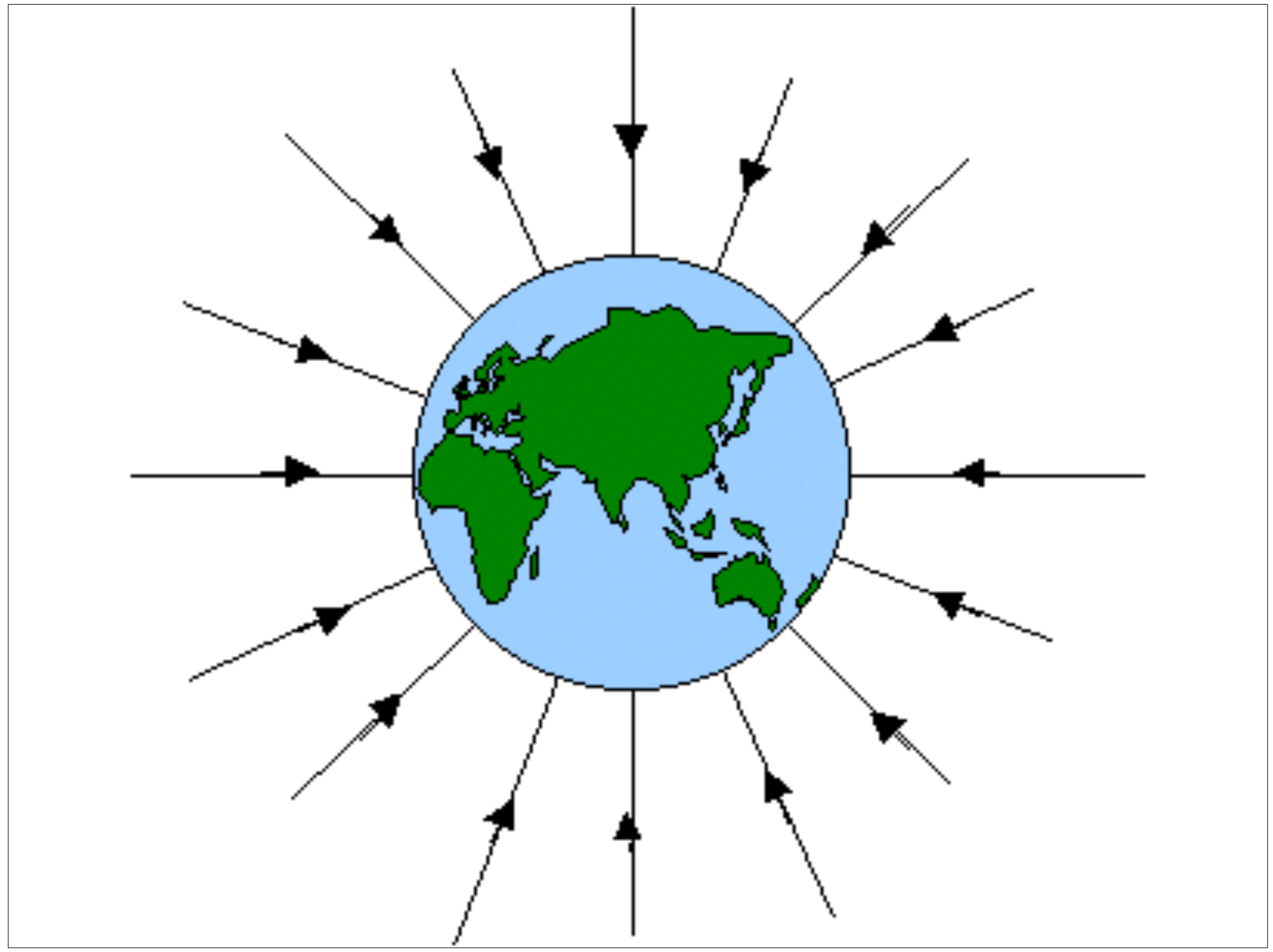
Field – (in physics) a physical quantity that has a value for every point in space and time

- You can pick any point in space at any time, and I can give you value (so, a number) and possibly a direction to represent that field

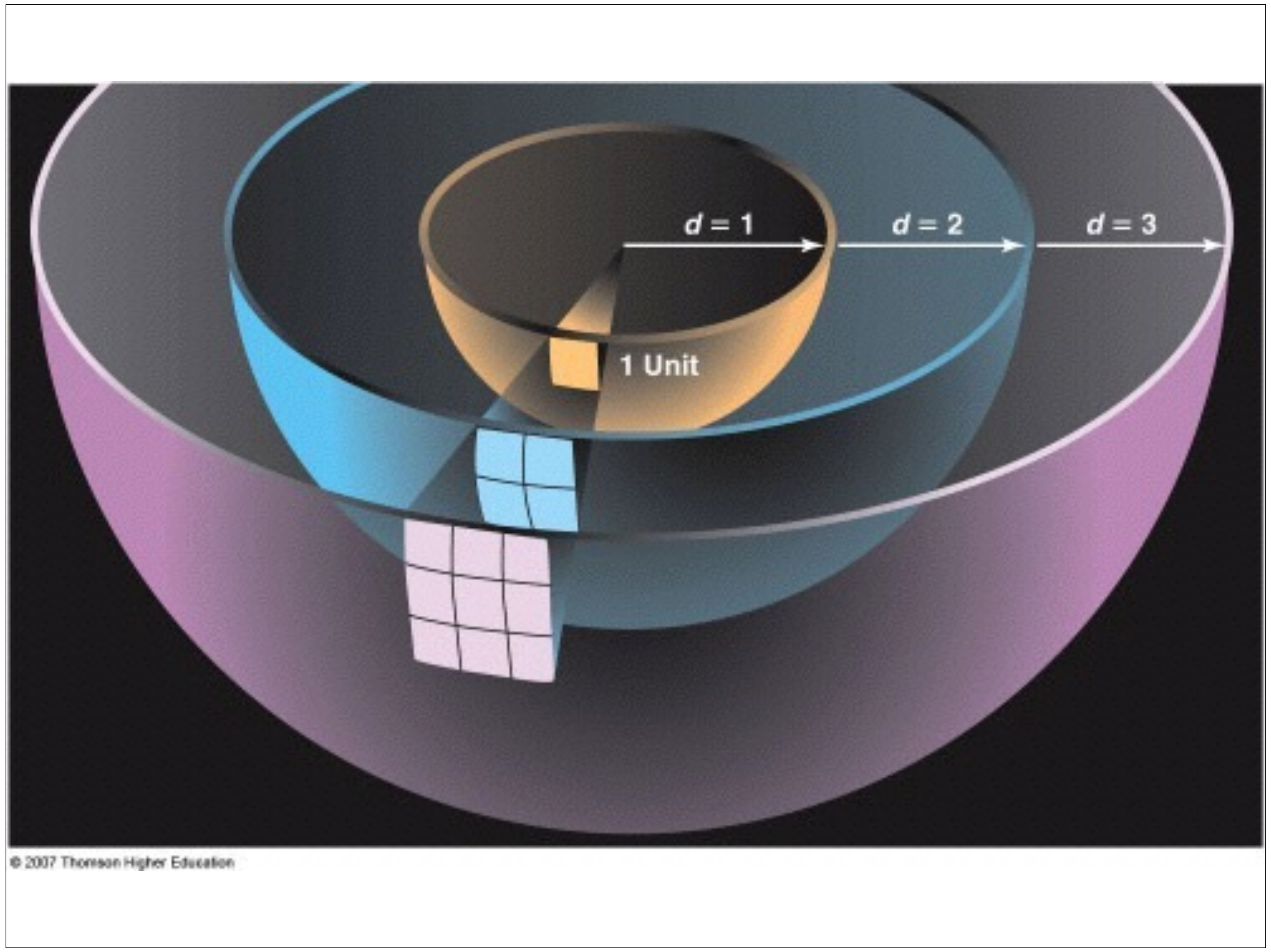
- Here's a map of a wind velocity field. A handful of the speeds are labeled and the lines and arrows indicate direction



- Here's a map of an electric field around two opposite electric charges. In this case, magnitude isn't labeled, but the arrows still show direction — not the direction of air molecules like in the last map, but the direction a positive charge would move if plopped into the electric field

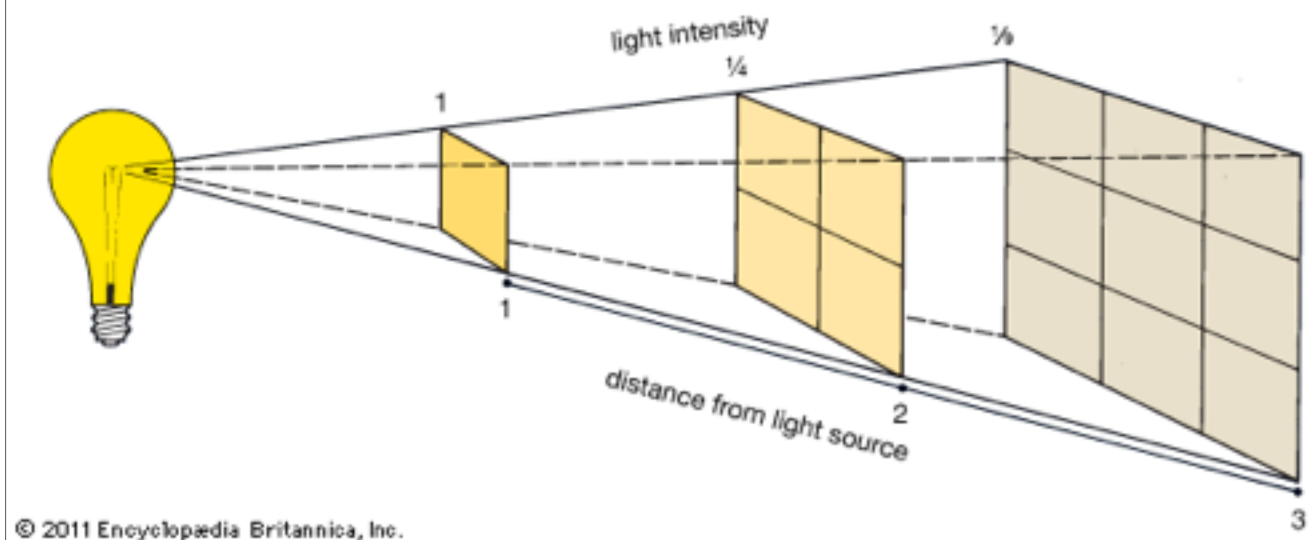


- Here’s a gravitational field map, where the arrows indicate which direction a mass would move under the influence of gravity
- Even though magnitude isn’t labeled, we know the field gets weaker and weaker as we move further from Earth (just as Earth’s gravitational influence gets weaker and weaker)



- One of the most important principles in physics is one based on simple geometry: the inverse square law
- The electric force, magnetic force, gravitational force, light intensity, sound intensity, radiation intensity, and others all share a common geometric principle: they generate a field or a wave front in all directions, and the intensity of that field or wave diminishes as it spreads out over more and more distance

INVERSE SQUARE LAW

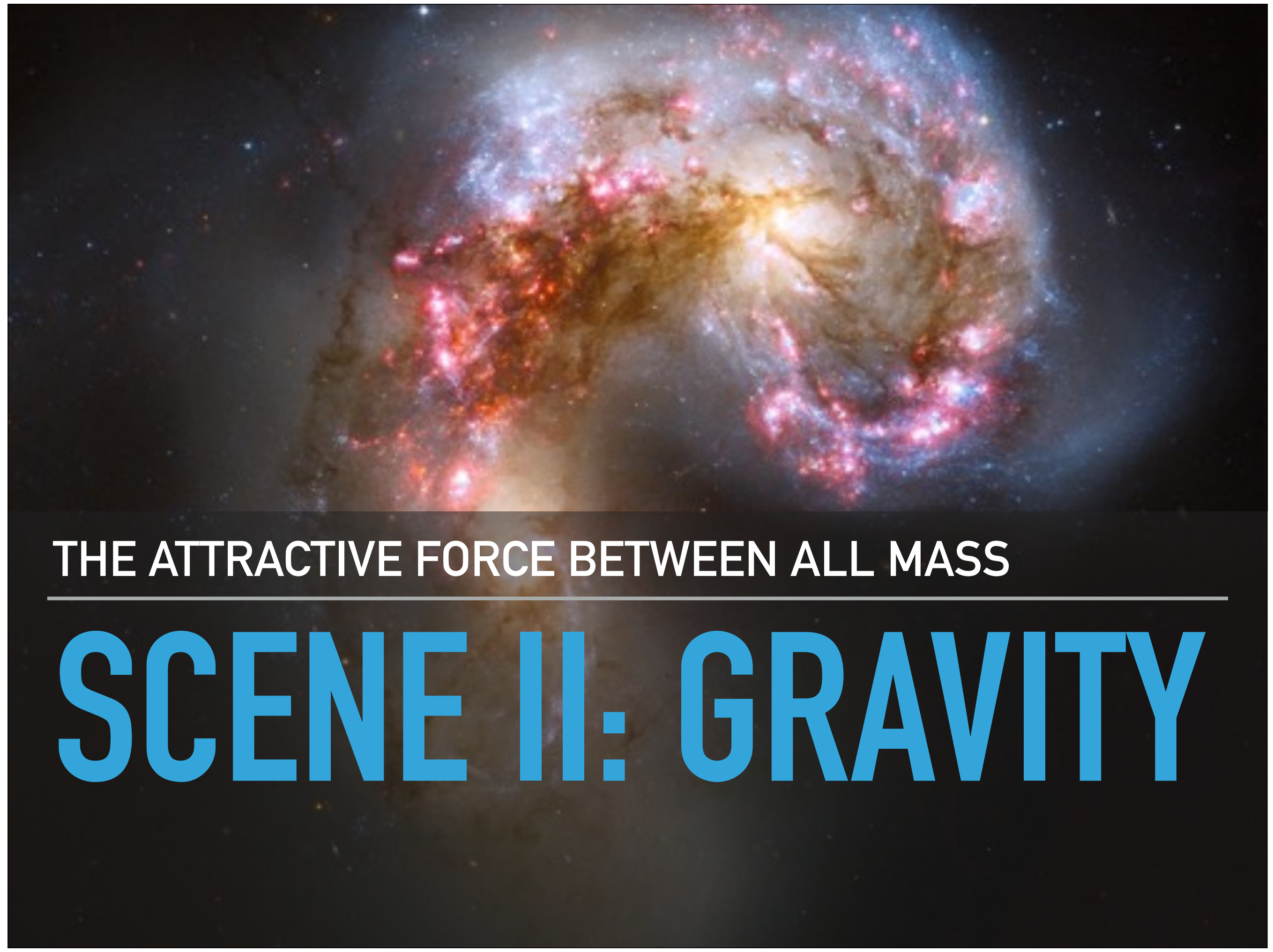


INVERSE SQUARE LAW

- (Use a piece of paper to show how when you half the distance to the projector, the image of the pup is only a forth as big but is four times as bright)

Four Fundamental Forces of Fysics

Force	Particles Experiencing	Force Carrier Particle	Range	Relative Strength*
Gravity acts between objects with mass	all particles with mass	graviton (not yet observed)	infinity	much weaker
Weak Force governs particle decay	quarks and leptons	W^+, W^-, Z^0 (W and Z)	short range	
Electromagnetism acts between electrically charged particles	electrically charged	γ (photon)	infinity	
Strong Force** binds quarks together	quarks and gluons	g (gluon)	short range	much stronger


THE ATTRACTIVE FORCE BETWEEN ALL MASS
SCENE II: GRAVITY

- Ted-Ed: Scientific Law vs. Theory
- https://www.youtube.com/watch?v=GyN2RhbhiEU

IF I HAVE SEEN FURTHER THAN OTHERS, IT IS BY STANDING ON THE SHOULDERS OF GIANTS

Isaac Newton

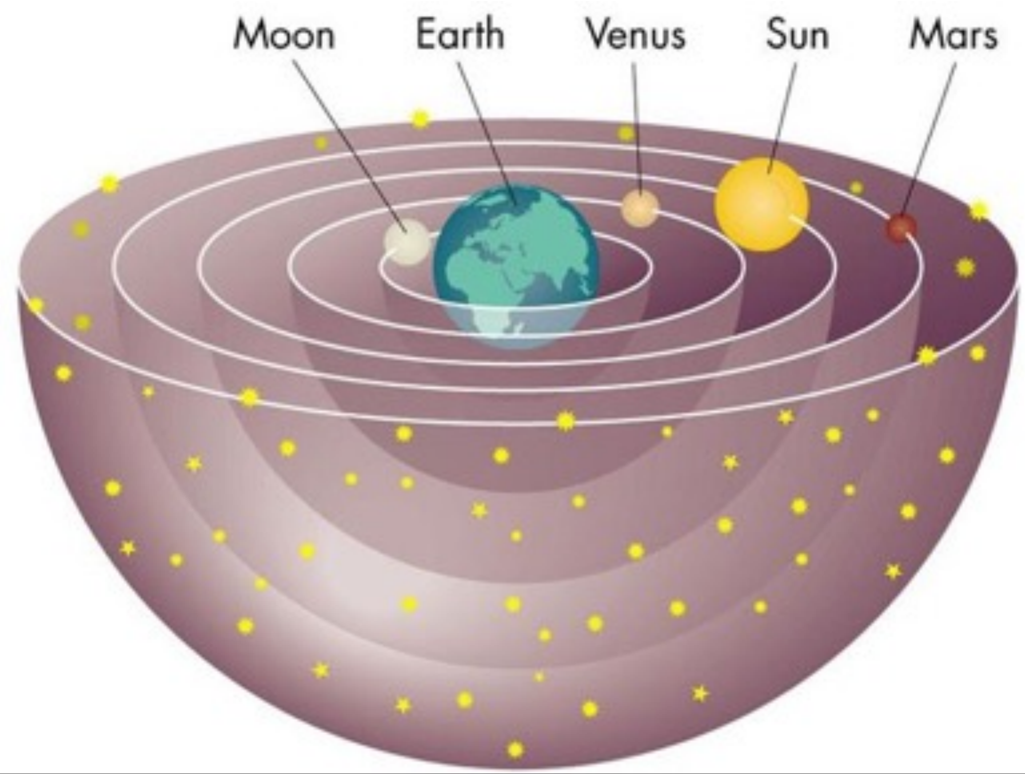

WHY?

CA. 100 - 170 AD

PTOLEMY

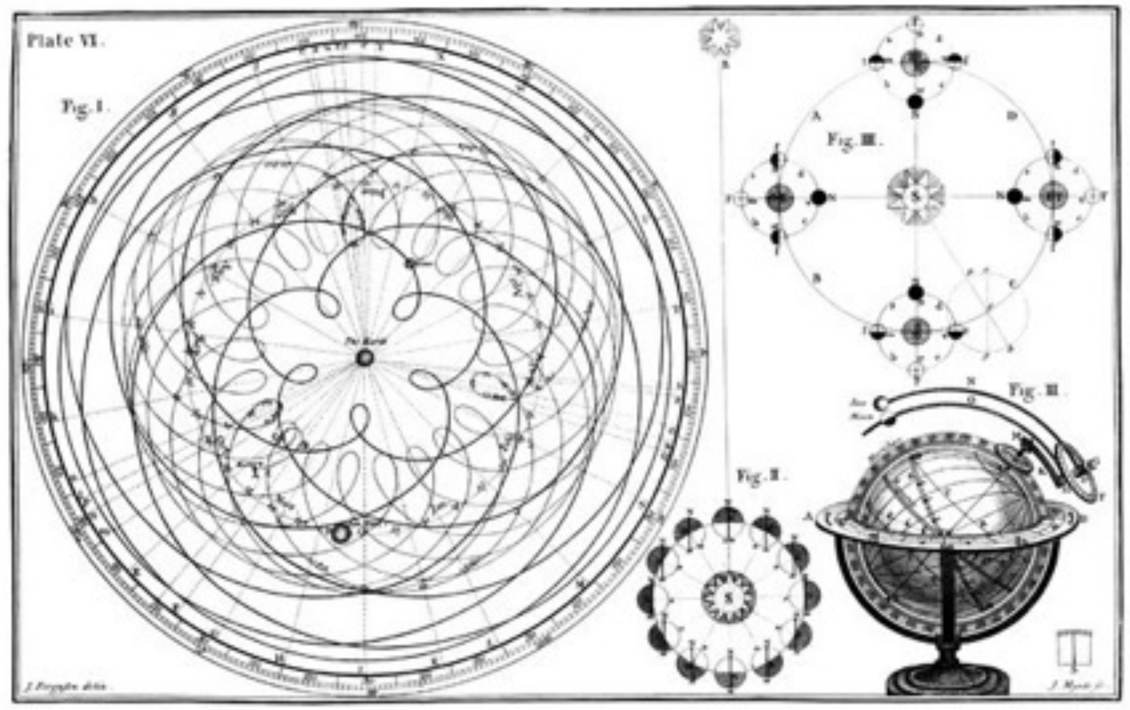
- Greco-Egyptian mathematician, astronomer, geographer, astrologer, and poet
- Developed his *Planetary Hypotheses* which provided the conventional model of the Universe for the next millennium and a half

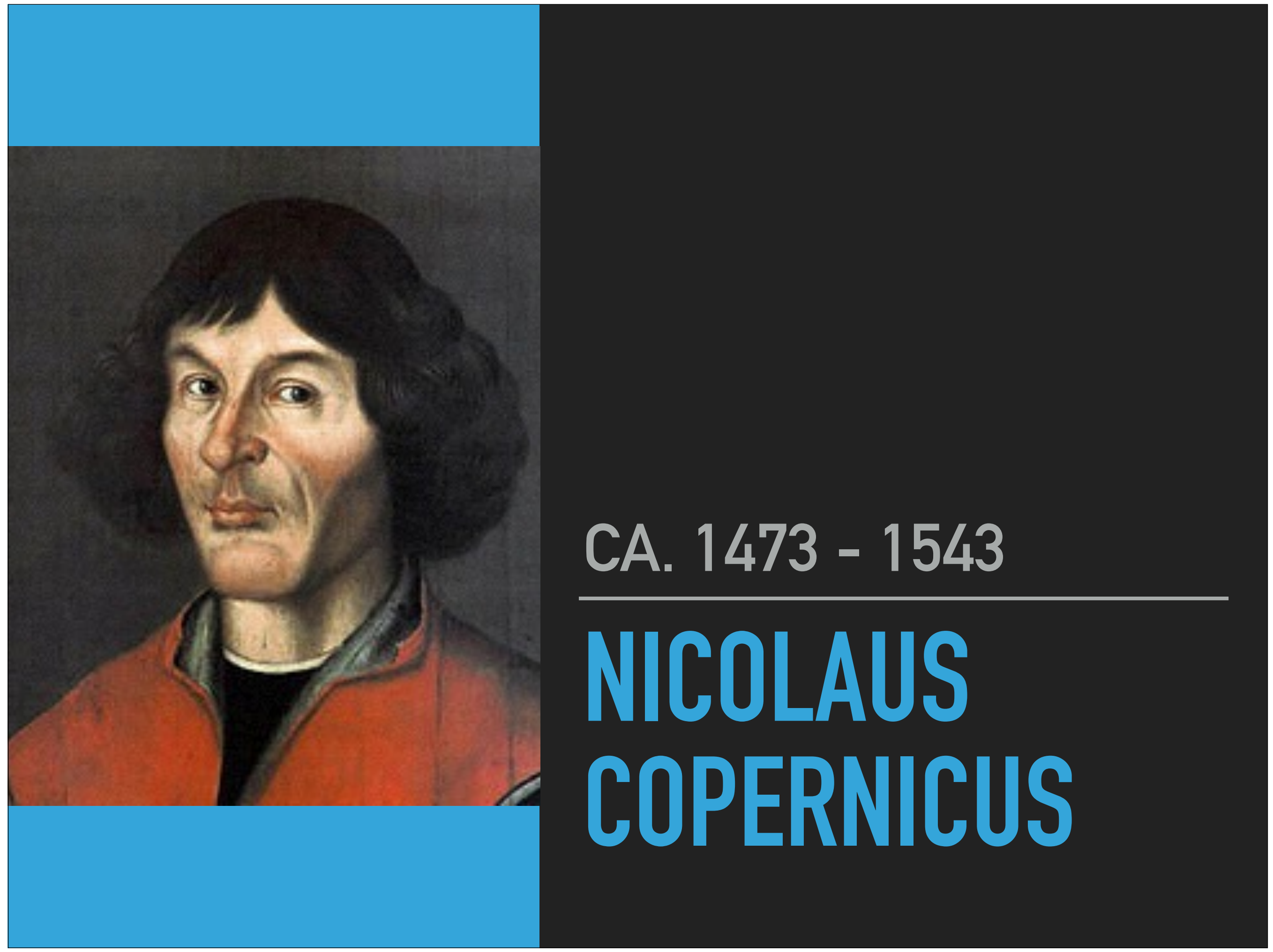
THE GEOCENTRIC MODEL



- Consisted of concentric shells, called celestial spheres, with the Earth at the center
    - *Geocentric Theory*
- The Sun and other planets orbit the Earth
- The stars are fixed to the outmost shell

ORBITS UNDER GEOCENTRIC THEORY



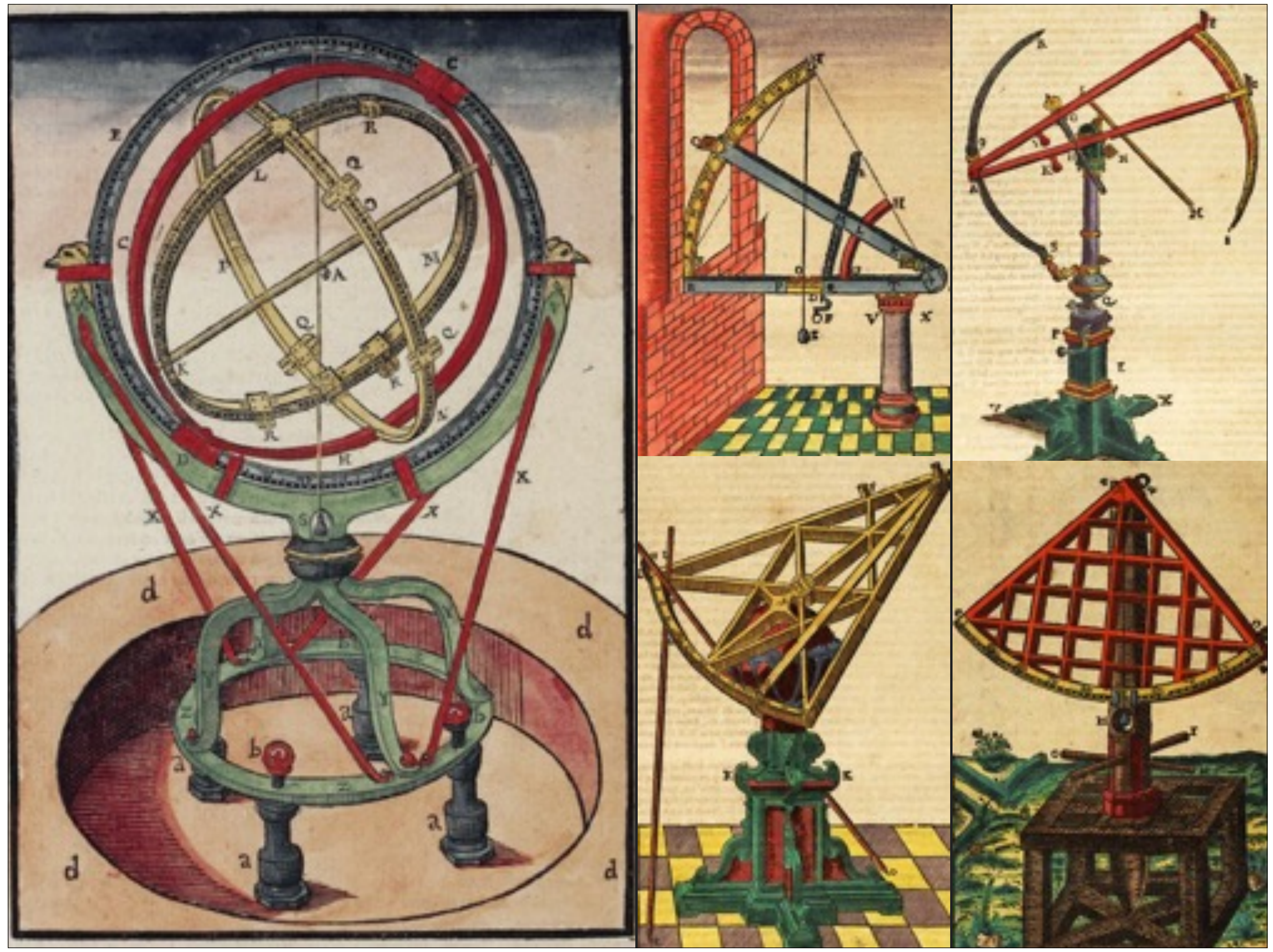


- Polish mathematician and astronomer
- Father of the *Heliocentric Theory* (Earth goes around the Sun, not vise versa)
- Often cited as the beginning of the Scientific Revolution

CA. 1546 - 1601

TYCHO BRAHE

- Danish astronomer, astrologer, and alchemist
- Meticulously recorded the positions of the planets and stars



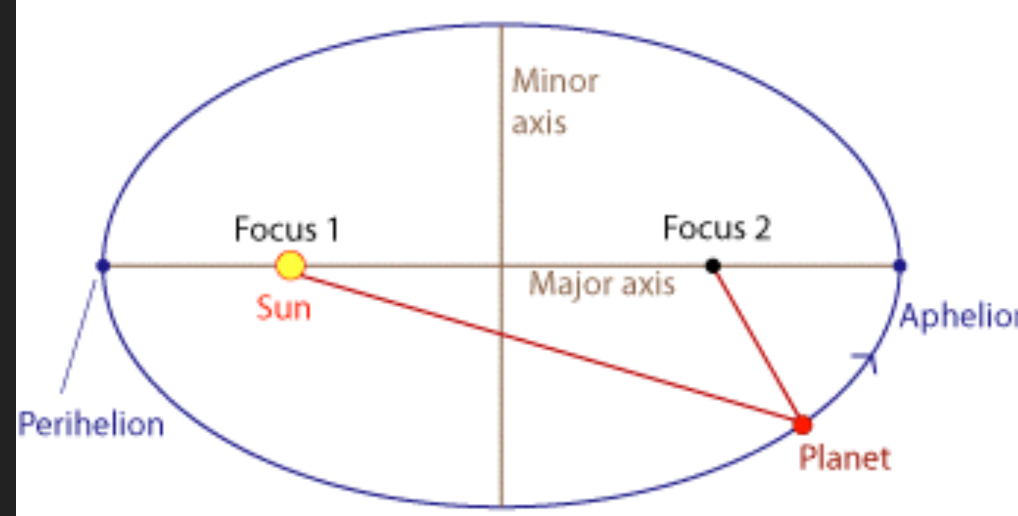
- What Brahe’s instruments are and what they do: https://www2.hao.ucar.edu/Education/FamousSolarPhysicists/tycho-brahes-observations-instruments

CA. 1571 - 1630

JOHANNES KEPLER

- German mathematician, astronomer, and astrologer
- Assistant to Tycho Brahe
- Used Brahe’s data to develop his own *Laws of Planetary Motion*

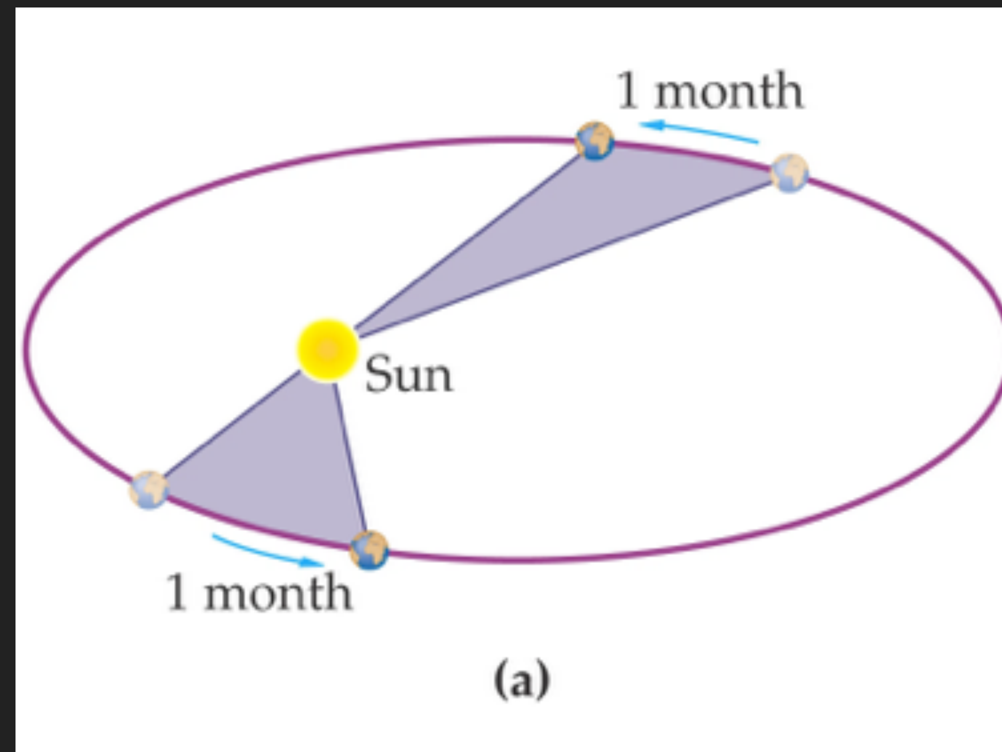
KEPLER'S 1ST LAW



An elliptical orbit of a planet
(greatly exaggerated)

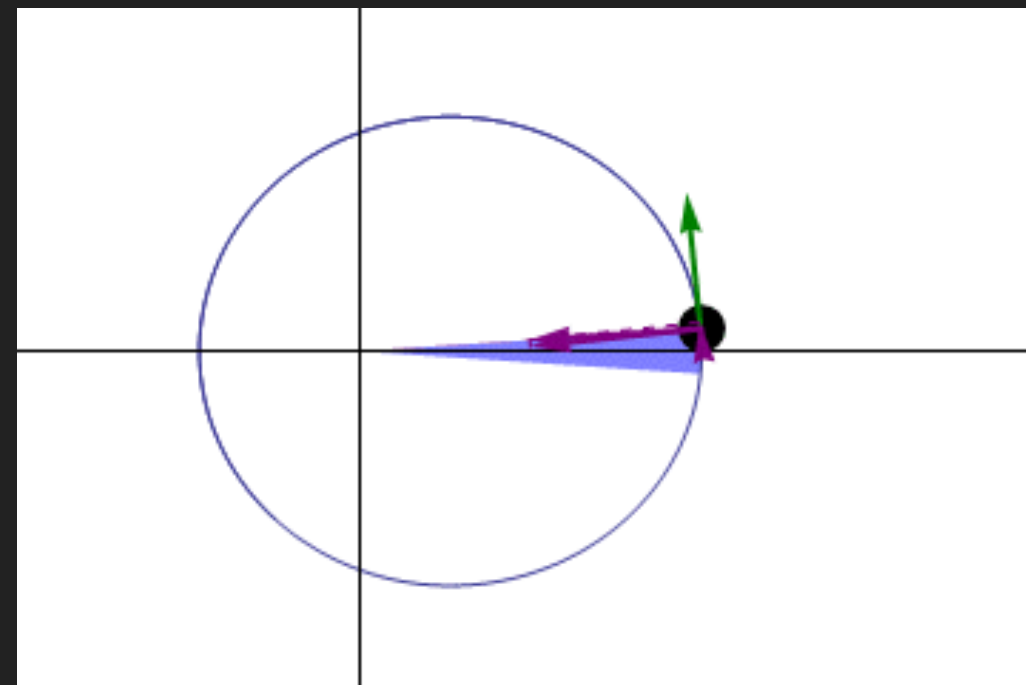
- The orbit of a planet is an ellipse with the Sun at one of the two focus points
- Discovered through trial and error

KEPLER'S 2ND LAW



- A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time

KEPLER'S 2ND LAW

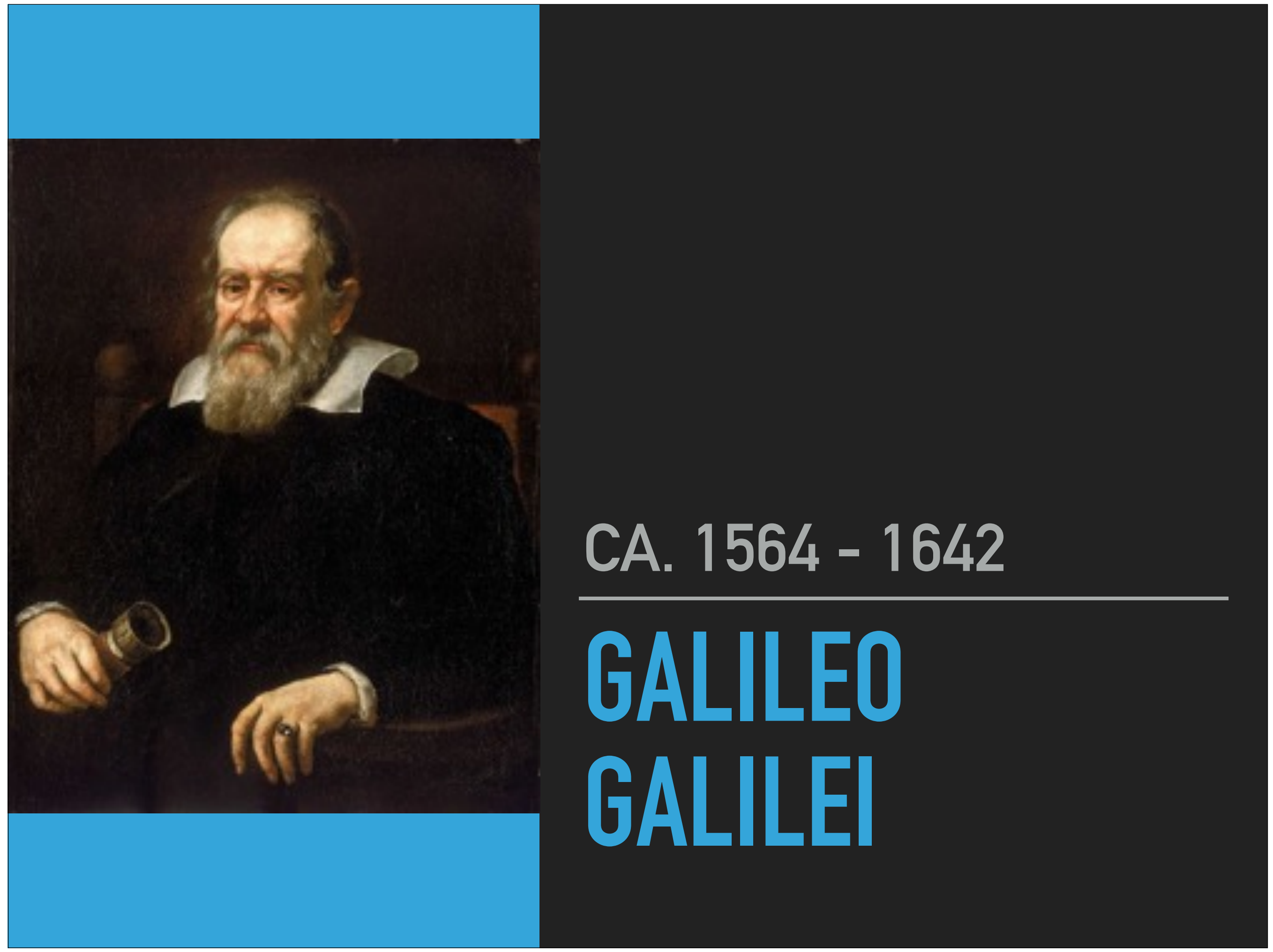


KEPLER'S 3RD LAW

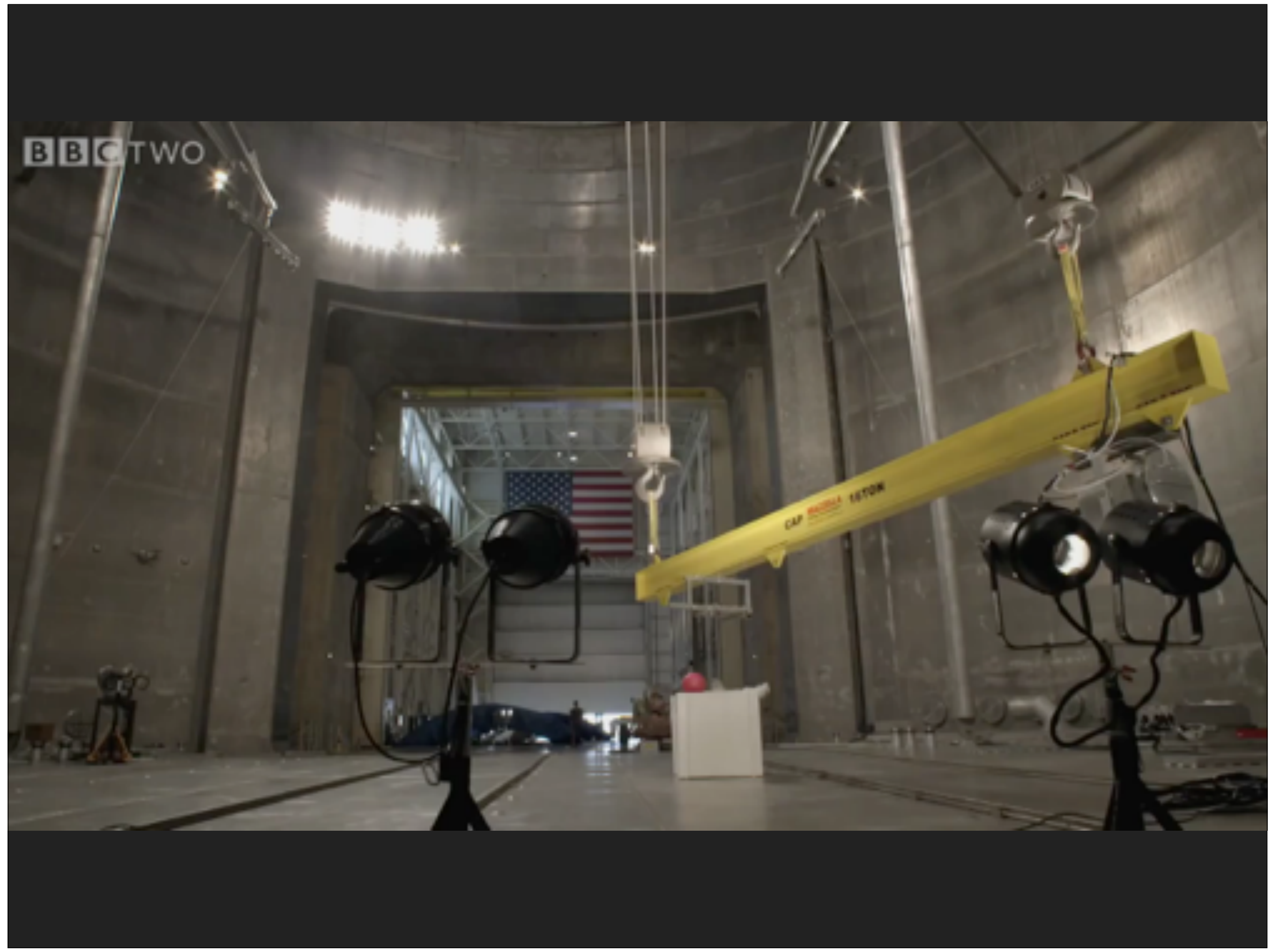
$$T^2 \propto r^3$$

*the **orbital period** of a planet **squared** is proportional to its **average distance** from the Sun **cubed***

- The time it takes a planet to go around the Sun and the size of the orbit are related

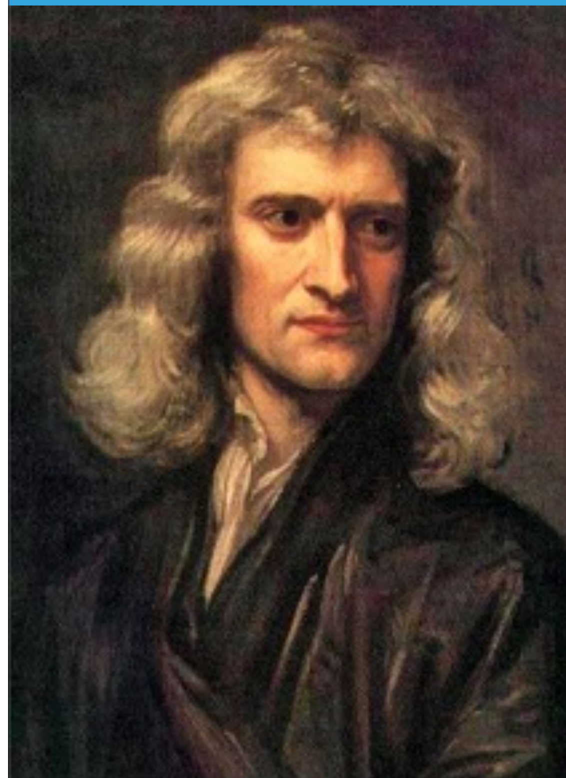


- Italian physicist, mathematician, engineer, astronomer, and philosopher
- In the absence of air resistance, all objects accelerate toward the Earth at the same rate, regardless of mass



- World’s largest vacuum chamber free fall demonstration
- https://www.youtube.com/watch?v=E43-CfukEgs

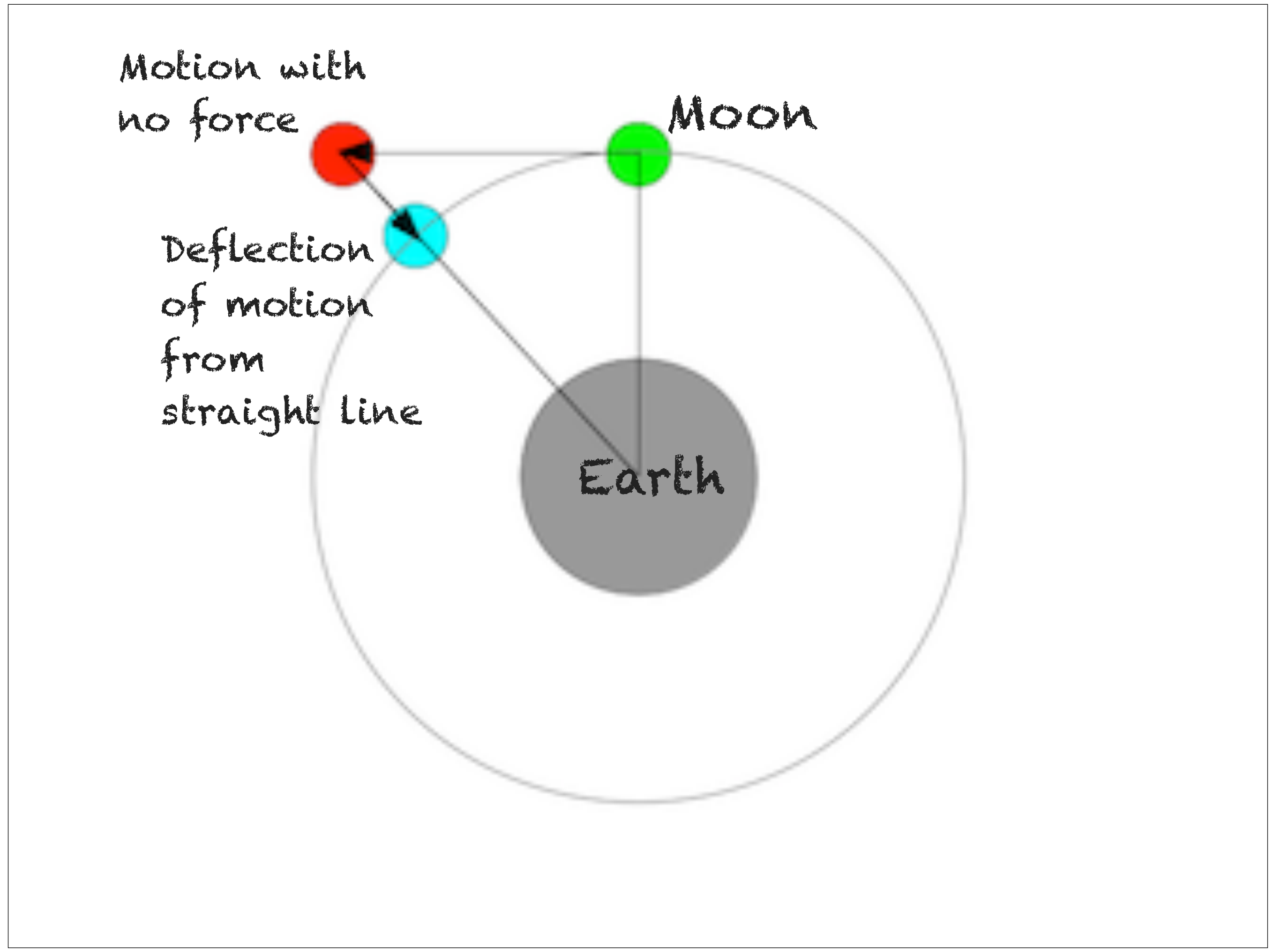
LAW OF INERTIA



CA. 1642 - 1726

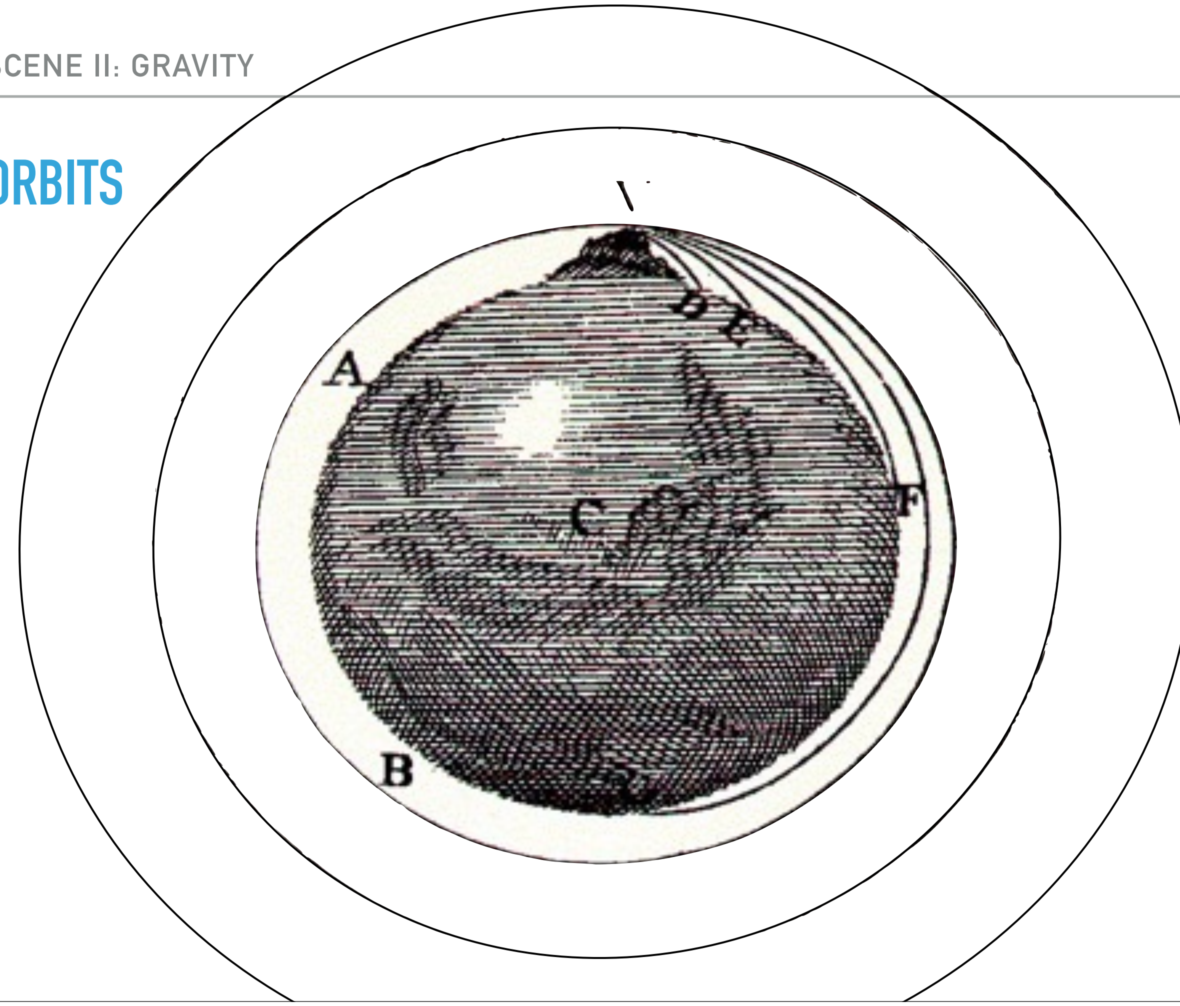
ISAAC NEWTON

- English physicist and mathematician
- Published *Principia* in 1687
  - Laws of Motion, foundation of classical mechanics, Law of Universal Gravitation, derivation of Kepler's Laws of Planetary Motion


Motion with
no force
Moon
Deflection
of motion
from
straight line
Earth

- Same phenomena that causes the apple to fall causes the moon to “fall”
- It doesn’t crash into the Earth because it has tangential velocity

ORBITS



- Newton used what he knew about circular motion to demonstrate that Kepler's 2nd Law is a consequence of the force always being pointed to whatever's being orbited

- The same reasoning Newton applied to the orbiting cannonball, he figured also applied to the Moon
- Since the same behavior is observed in the Moon orbiting the Earth as is observed in Jupiter’s moons orbiting it or the planets orbiting the Sun, Newton figured he could apply his logic there, too

SCENE II: GRAVITY

UNIVERSAL GRAVITY

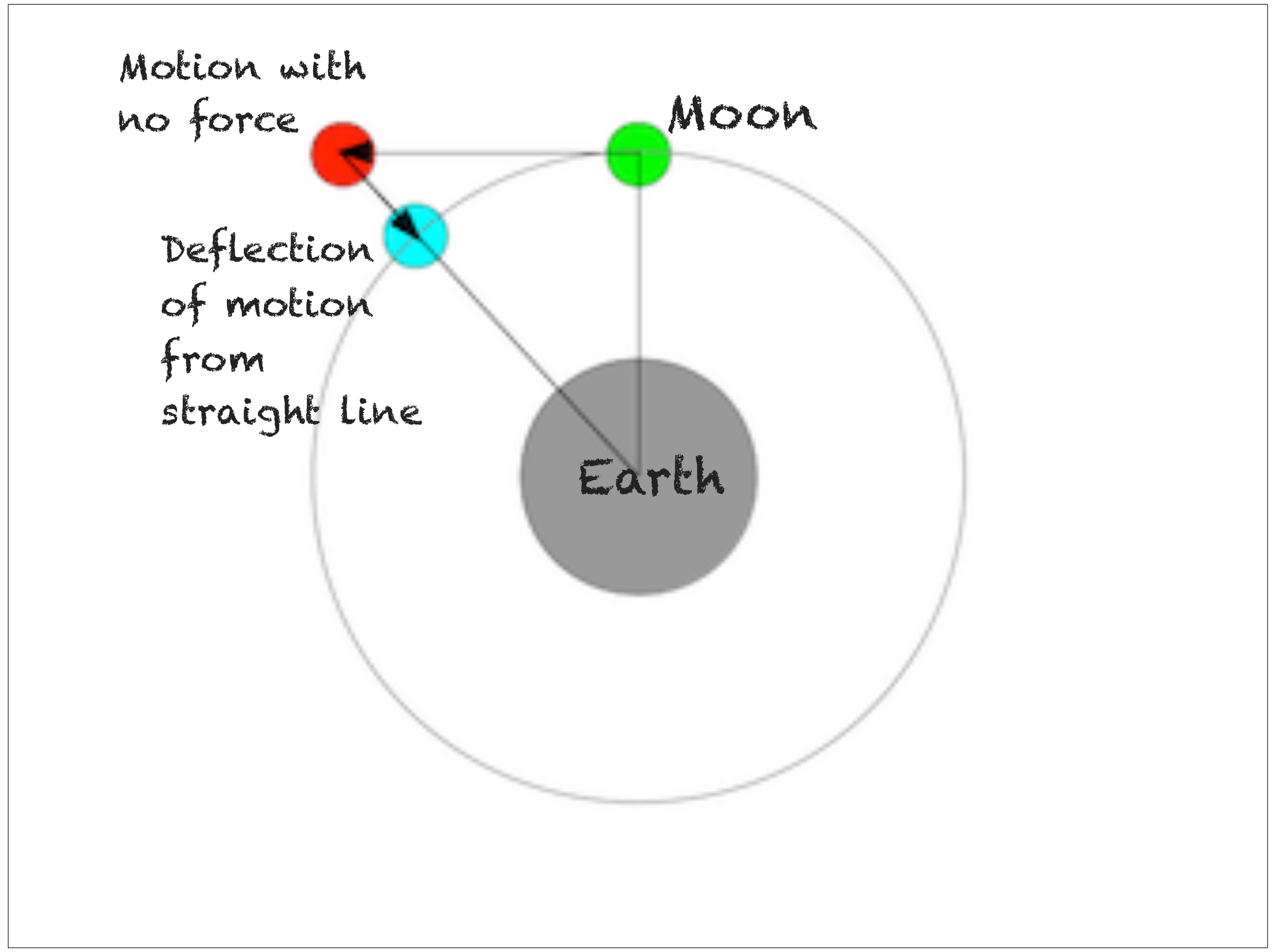
- In fact, Newton reasoned these rules applied to *anything* with mass

GRAVITY & INVERSE SQUARE LAW

$$F_g \propto \frac{m_1 m_2}{r^2}$$

*the **force of gravity** is proportional to the product of the **masses** & inversely proportional to the **distance squared***

- Circular motion plus Kepler's 3rd indicates that gravity obeys the inverse square law

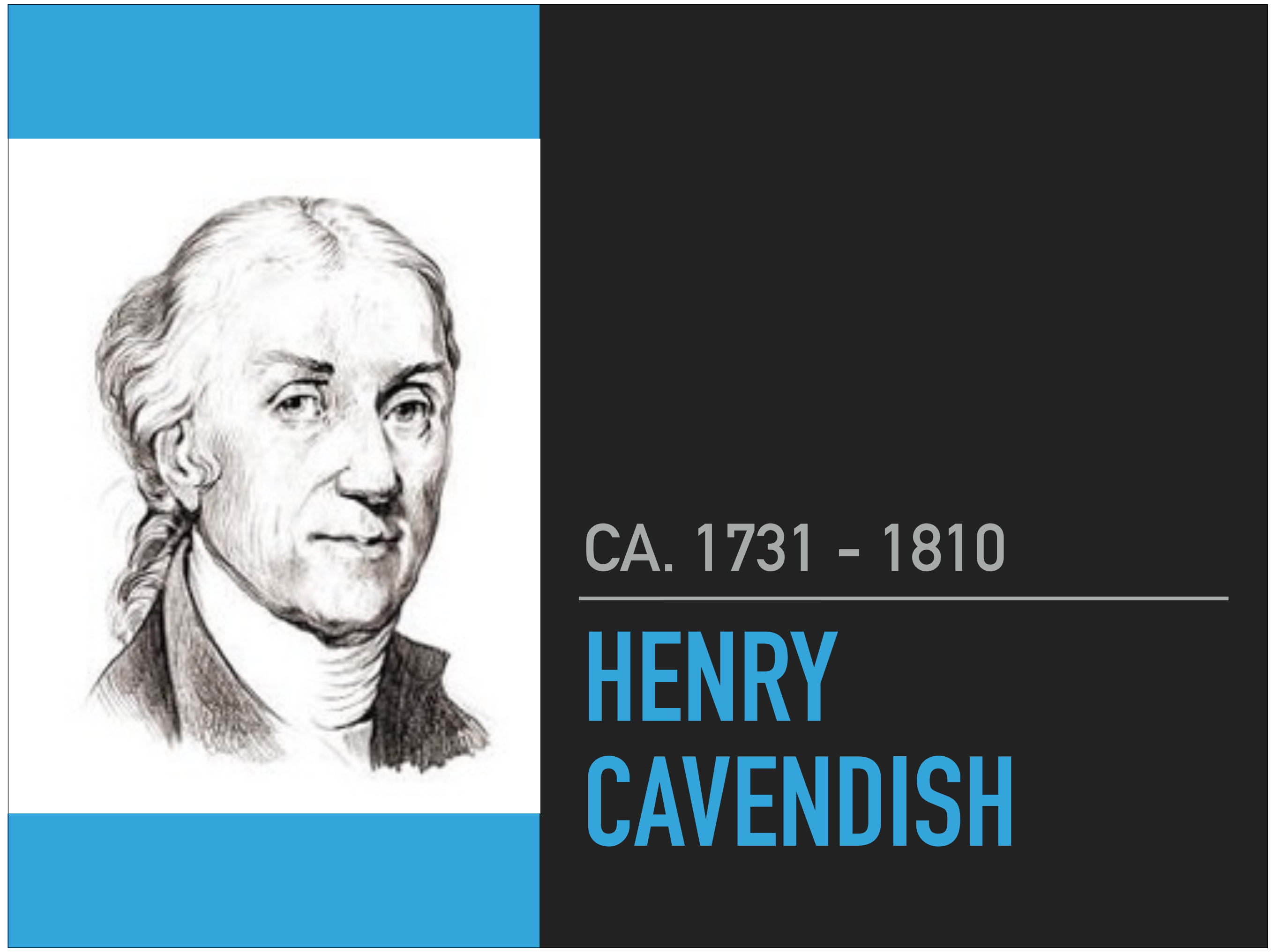


- Mass doesn't matter. Only distance, so compare the fall of an apple to fall of the Moon
  - Apple falls 4.9m in 1s
  - The Moon is 60x further from Earth
  - Moon falls 1.4mm$_2$
  - F_g is diluted by 1/r — QED

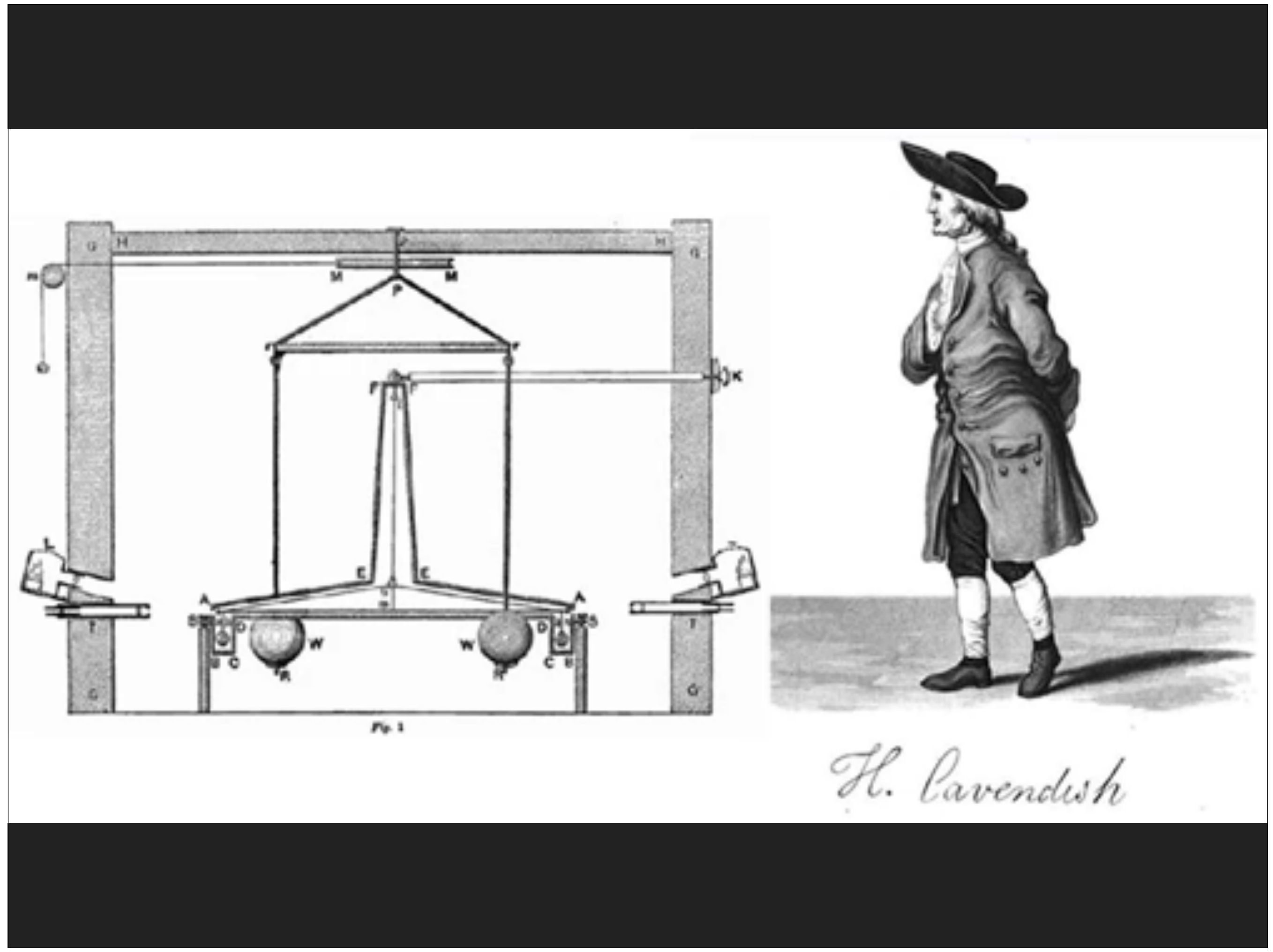
- M80: Globular Cluster in Scorpius
- 96 ly across (100,000 times as big as the solar system) and the same rules of gravity apply

- Typical galaxies are 50,000 to 100,000 ly across

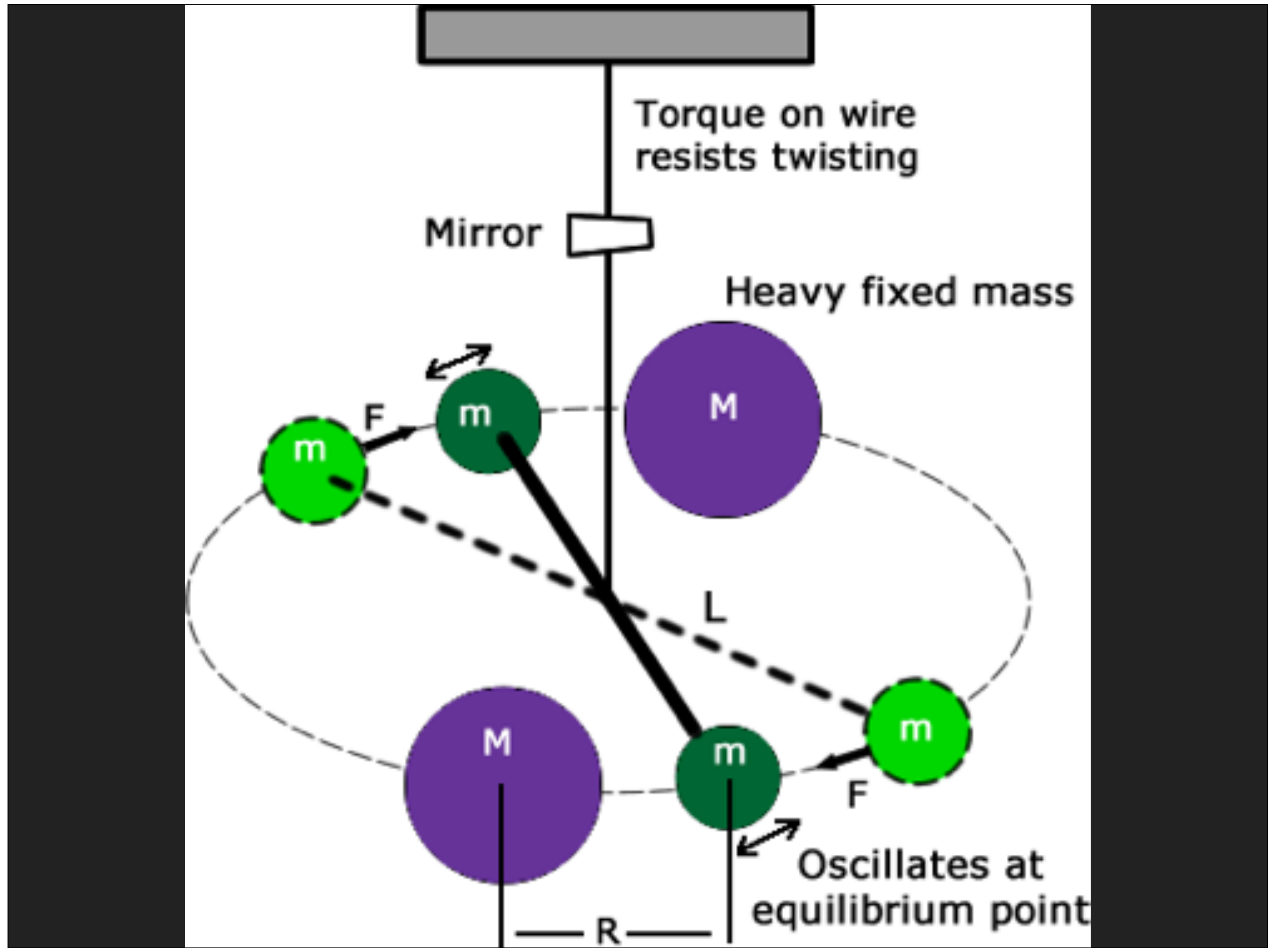
- Abell S0740 galaxy cluster
- e.g. the Milky Way and Andromeda galaxies are 2.5 million ly apart
- Even on these enormous scales, gravity is still the prevailing force!



- English physicist and chemist
- First direct test of the attraction between masses



- The Cavendish Experiment


Torque on wire
resists twisting
Mirror
Heavy fixed mass
F
m
m
M
L
M
m
m
F
Oscillates at
equilibrium point
R

LAW OF GRAVITY

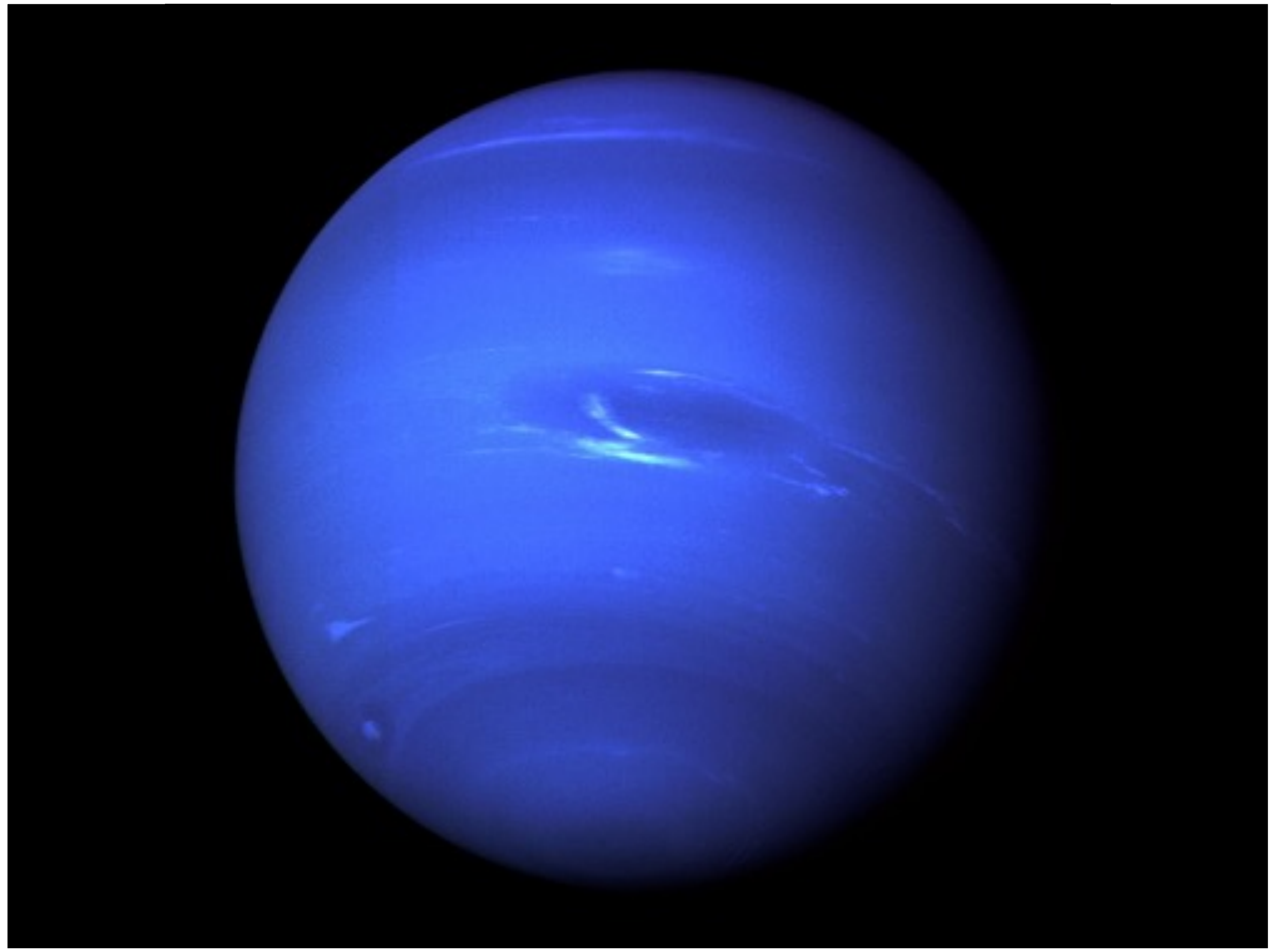
$$F_g = \frac{Gm_1m_2}{r^2}$$

where G $\approx 7 \times 10^{-11}$

- Gravity with Cavendish's constant of proportionality

WEIGHING THE EARTH

- Newton's 2nd Law plus Law of Gravity allows us to deduce the mass of the planet!
- $R_{\text{earth}} \approx$ 6,000 km
  - $M_{\text{earth}} \approx 5\text{x}10^{24}$ kg



- In 1821, Alexis Bouvard observed disturbances in the orbit of Uranus
- Newton’s theory of gravity predicted these disturbances were due to the presence of an unknown gravitational source and eventually led to the discovery of Neptune

NINTH PLANET?

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01/20/2016

Caltech Researchers Find Evidence of a Real Ninth Planet

Caltech researchers have found evidence of a giant planet tracing a bizarre, highly elongated orbit in the outer solar system. The object, which the researchers have nicknamed Planet Nine, has a mass about 10 times that of Earth and orbits about 20 times farther from the sun on average than does Neptune (which orbits the sun at an average distance of 2.8 billion miles). In fact, it would take this new planet between 10,000 and 20,000 years to make just one full orbit around the sun.

The researchers, Konstantin Batygin and Mike Brown, discovered the planet's existence through mathematical modeling and computer simulations but have not yet observed the object directly.

This artistic rendering shows the distant view from Planet Nine back towards the sun. The planet is thought to be gaseous, similar to Uranus and Neptune. Hypothetical lightning lights up the night side.

Credit: Caltech/R. Hurt (IPAC)

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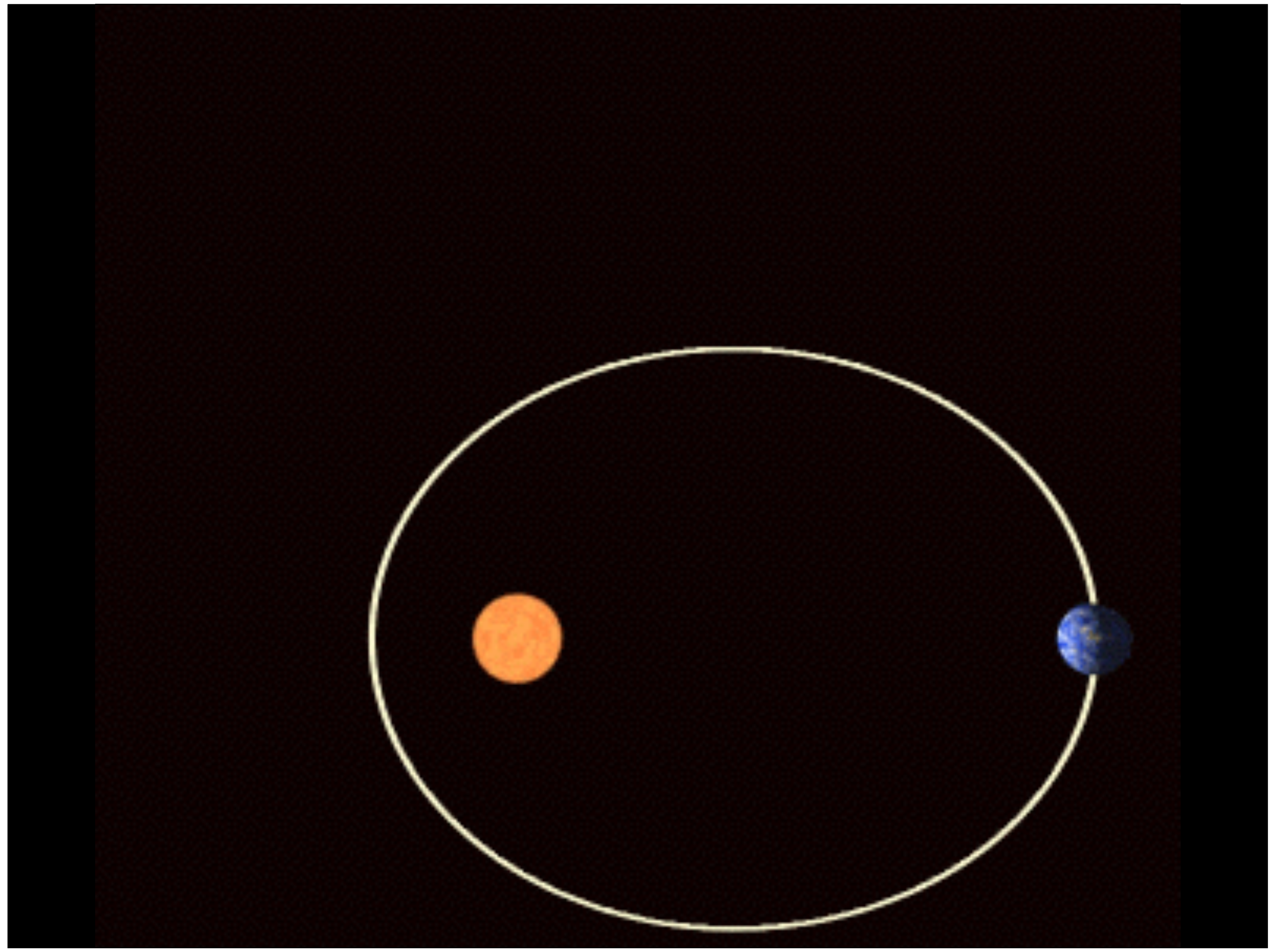
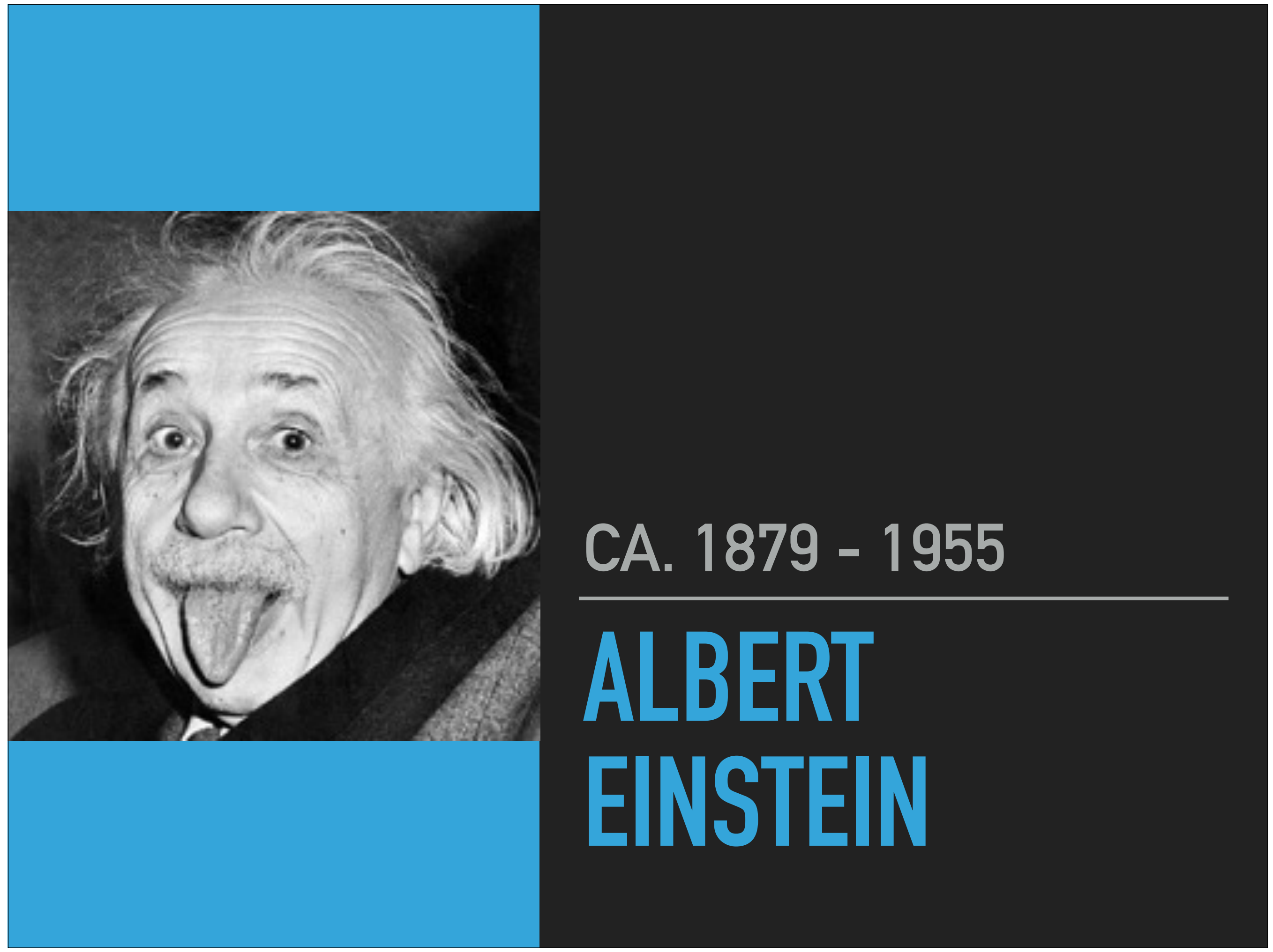
- https://www.caltech.edu/news/caltech-researchers-find-evidence-real-ninth-planet-49523
- Responsible for apparent tilt of Sun and disturbances in Kuiper Belt?



- However, Newton's theory could not accurately account for Mercury's eccentric orbit



- German theoretical physicist and philosopher of science
- Gravity as curvature of spacetime
- Einstein’s theory of general relativity explained the precession of Mercury’s orbit is due to the severely curved spacetime near the Sun

- Spacetime curvature demo
- https://www.youtube.com/watch?v=MTY1Kje0yLg

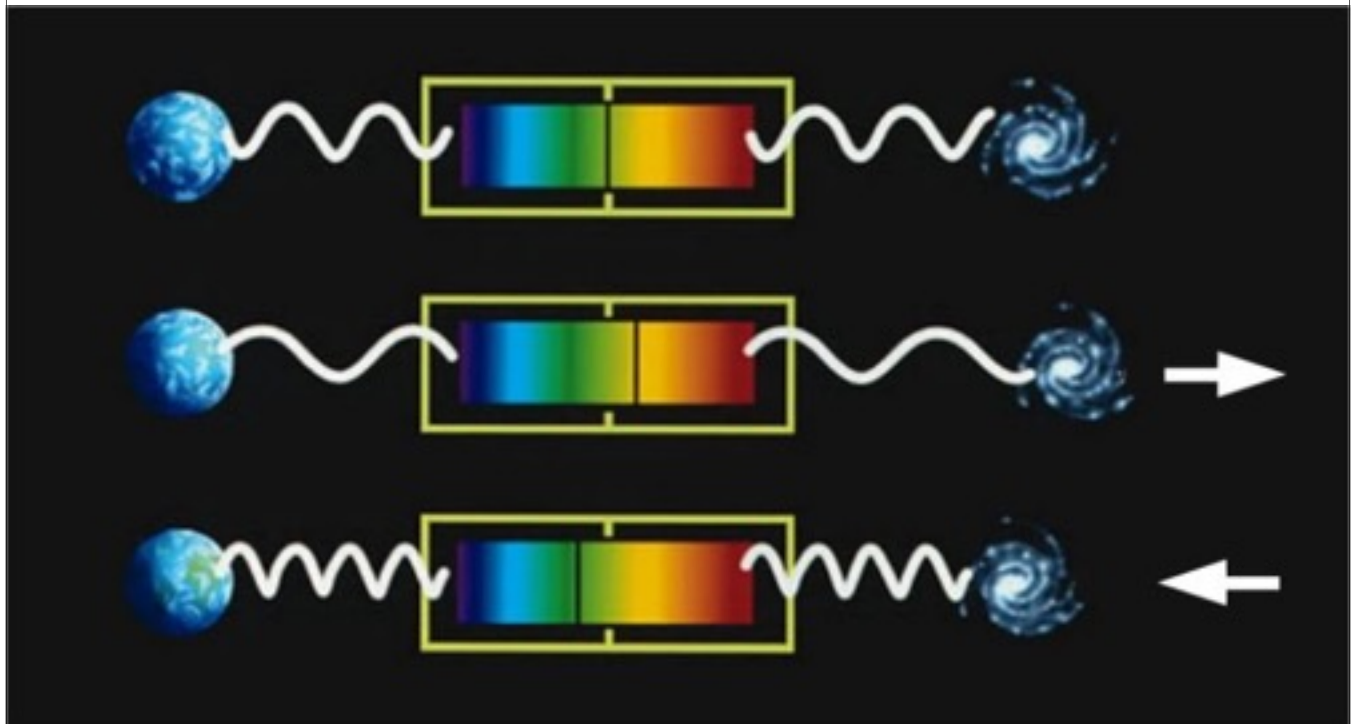
SCHWARZSCHILD METRIC

$$ds^2 = -\left(1 - \frac{2GM}{c^2 r}\right)(c\,dt)^2 + \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\varphi^2\right)$$

- Describes the geometry of spacetime around a star
- Super important in GPS navigation

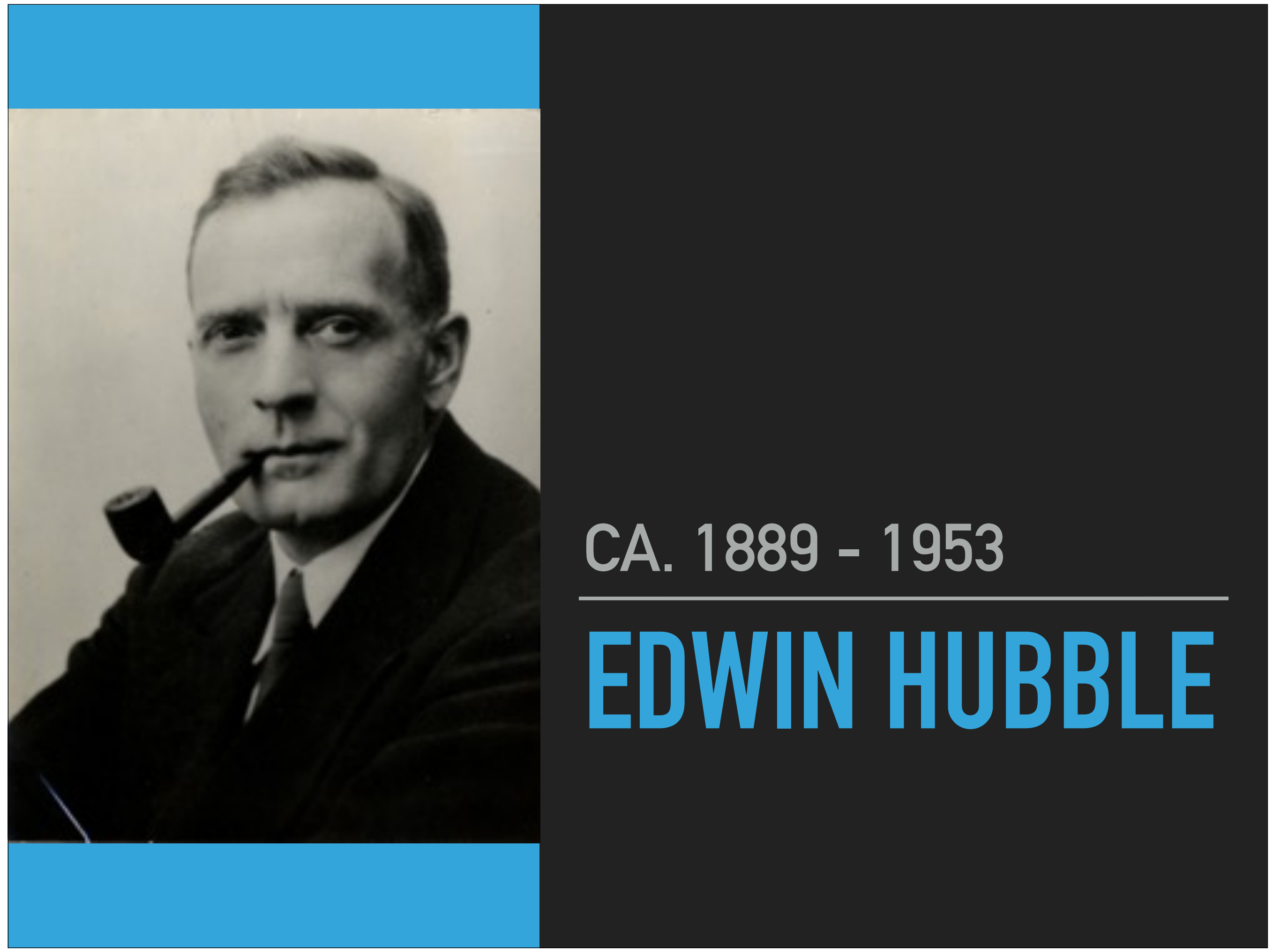
- American astronomer
- Performed first measurements of radial velocities for galaxies, providing the empirical basis for the expansion of the universe (ca. 1912-17)

REDSHIFT & BLUESHIFT



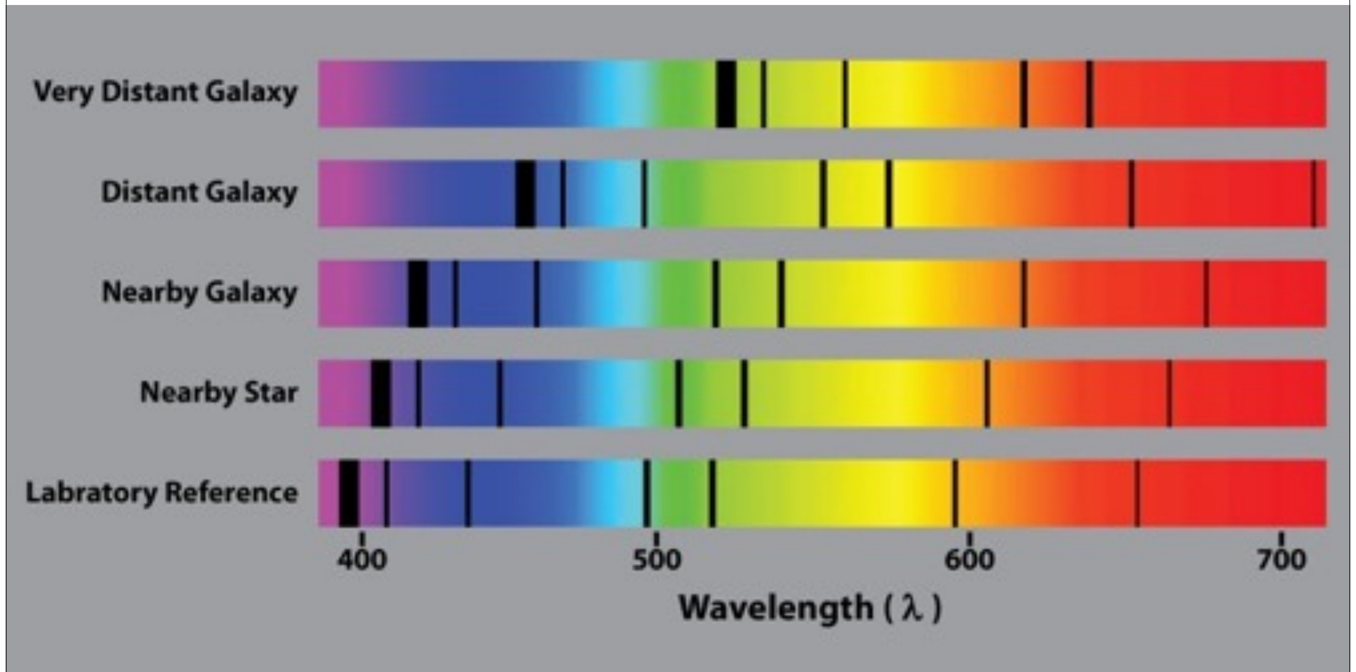
- When an object moves toward us, the light waves it emits bunch up making it look “bluer”
- When moving away, the light waves spread out making it look “redder”
- Everywhere Slipher looked, the galaxies all looked redshifted, implying they’re moving away from us

- Both scientists found that an expanding or contracting Universe fit the Einstein equations better
- Given the redshifts observed by Slipher, they proposed the Universe must be getting bigger

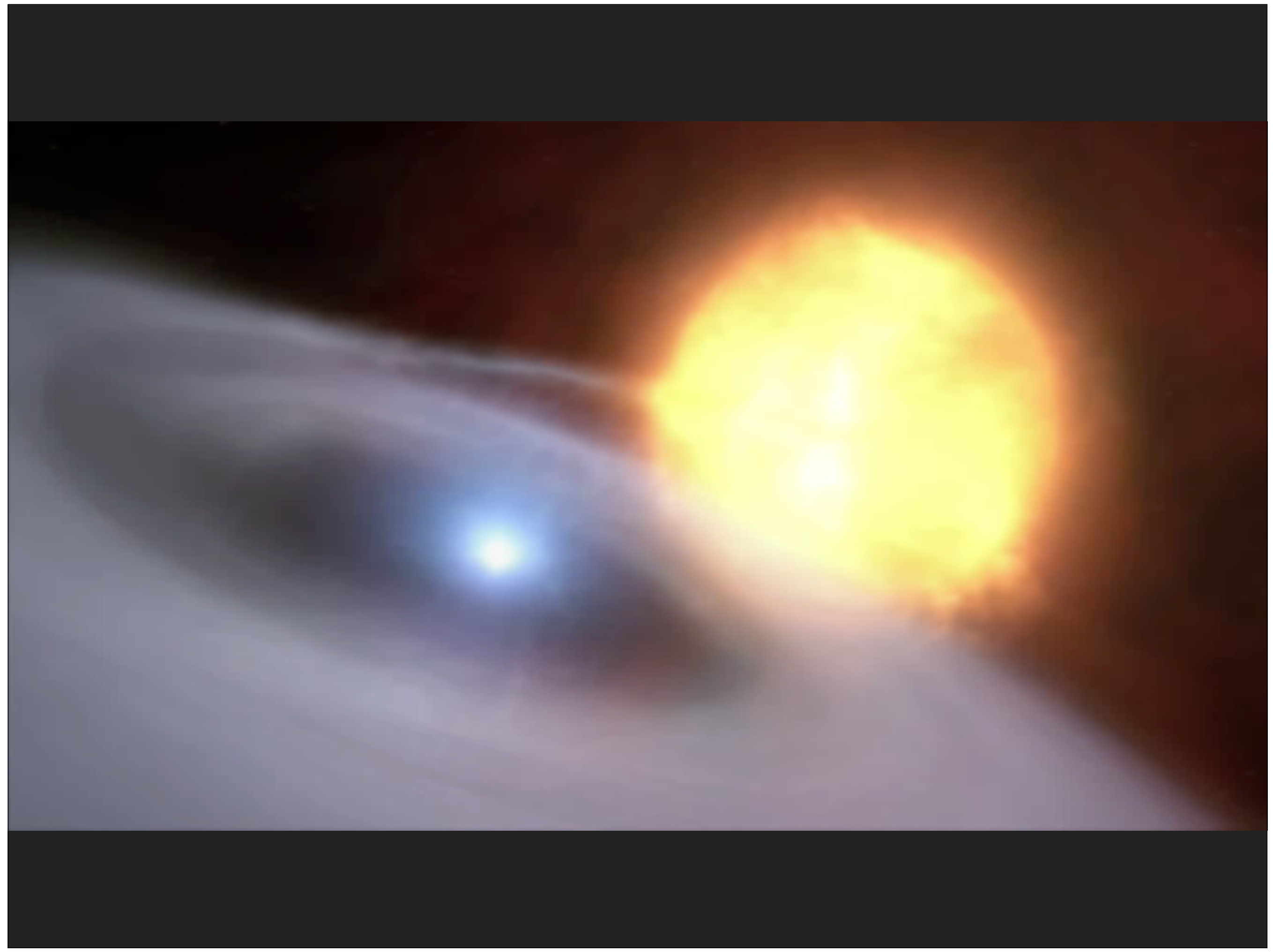


- American astronomer and cosmologist
- Discovered that previously observed “nebulae” were actually galaxies in their own right
- Found that the further away a galaxy was, the faster it was moving away from us

GALACTIC REDSHIFT



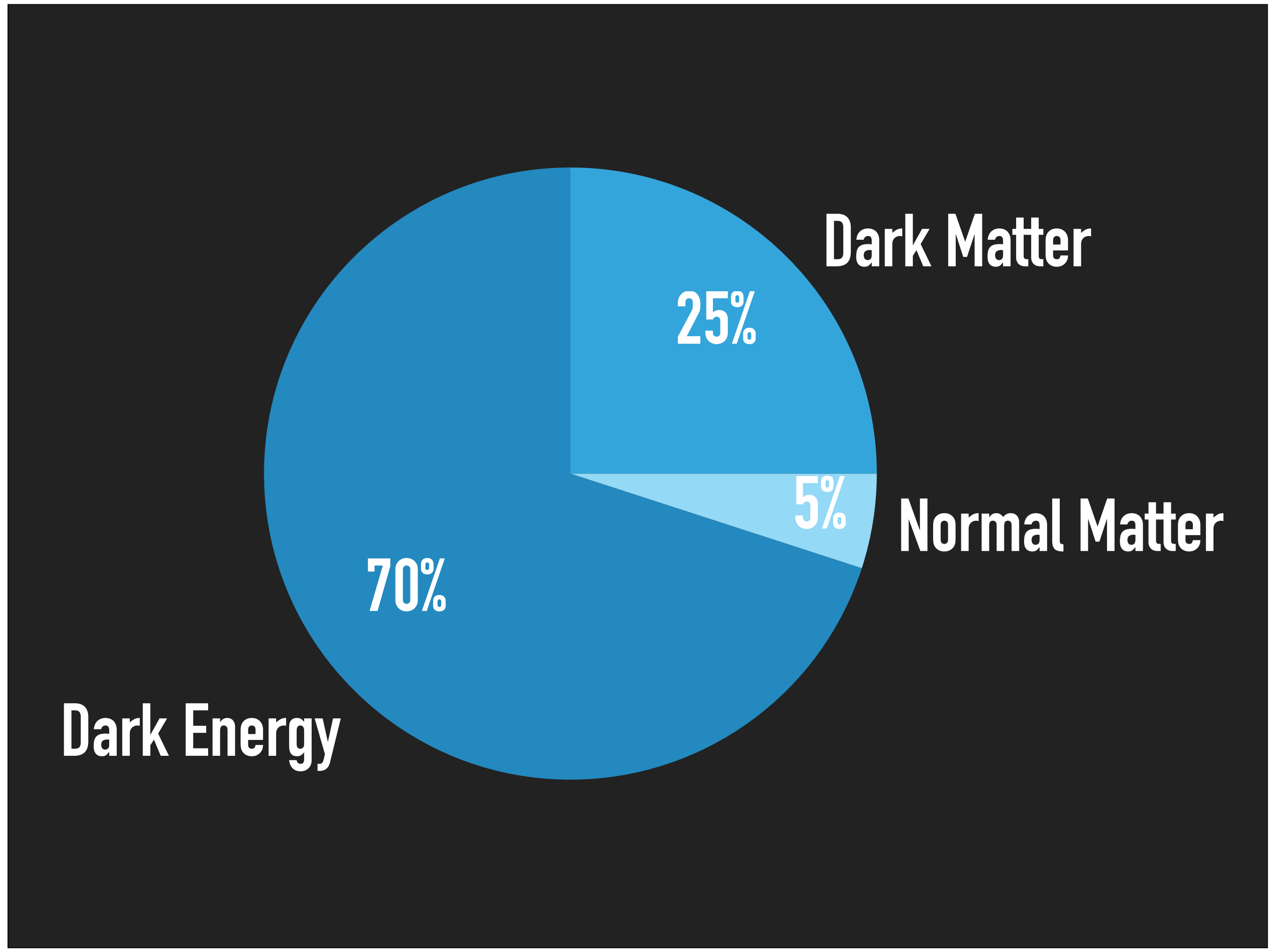
- This is true everywhere we look, confirming Lemaître & Friedmann's conclusions that the Universe is expanding



- In 1998, two independent teams observing extremely distant Type 1a Supernovae both found the supernovae were much further away than the redshift would suggest
- Both teams independently came to the same conclusion: the expansion of the Universe is accelerating

DARK ENERGY

- This mysterious energy permeating all of space causing it to expand has been dubbed *dark energy*



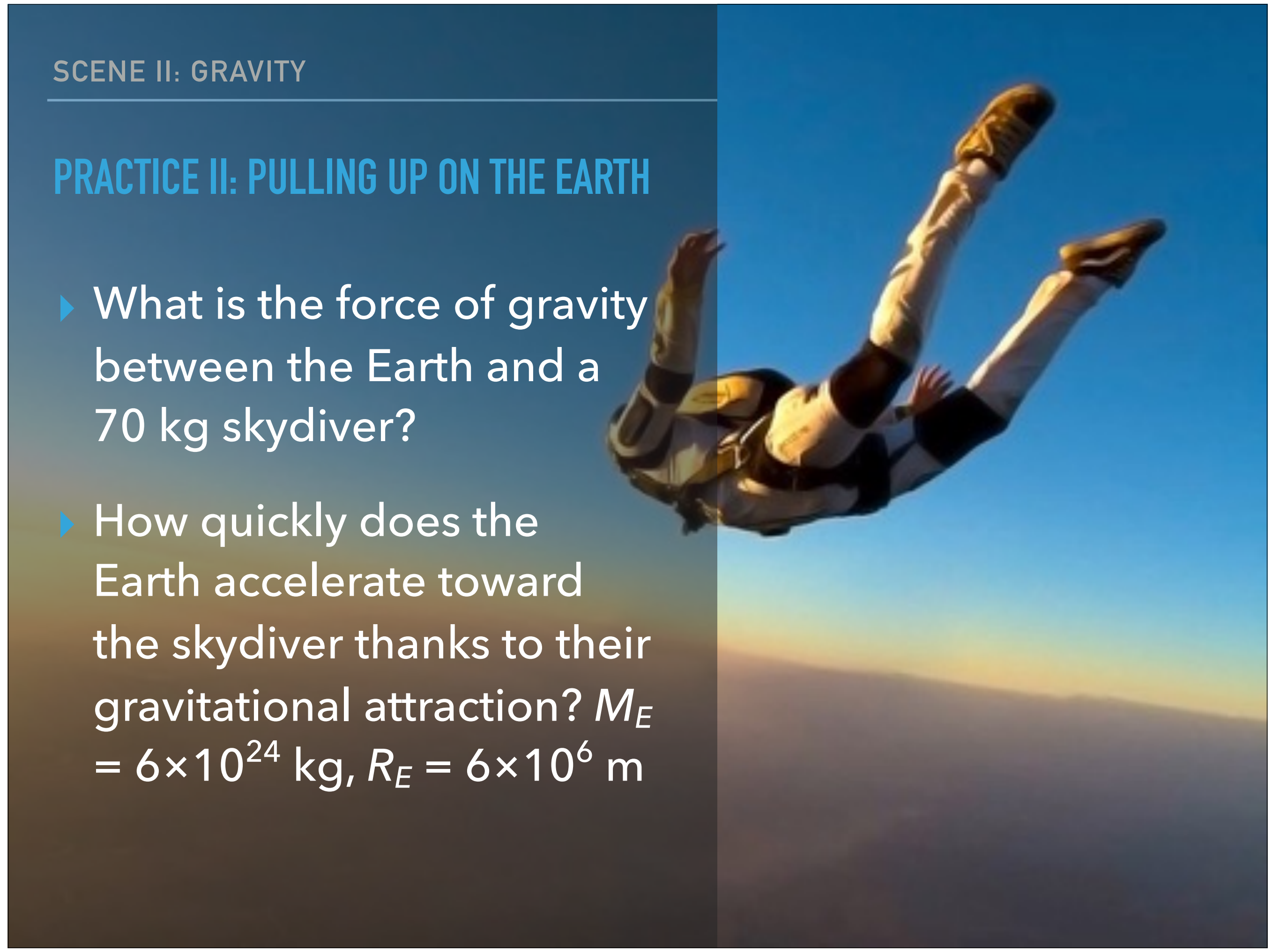
- Most of the Universe is stuff we can’t see

NEWTONIAN GRAVITY

PRACTICE I: GRAVITY BETWEEN STUDENTS

- What's the force of gravity between two students?
- m_1 = ______________
- m_2 = ______________
- r = ______________
- *Ans*: F_g = ____________

- Answer: $F_g \sim 10$ N



- Answer: $F_g \approx 700$ N; $a_g \approx 1\text{x}10$ m/s

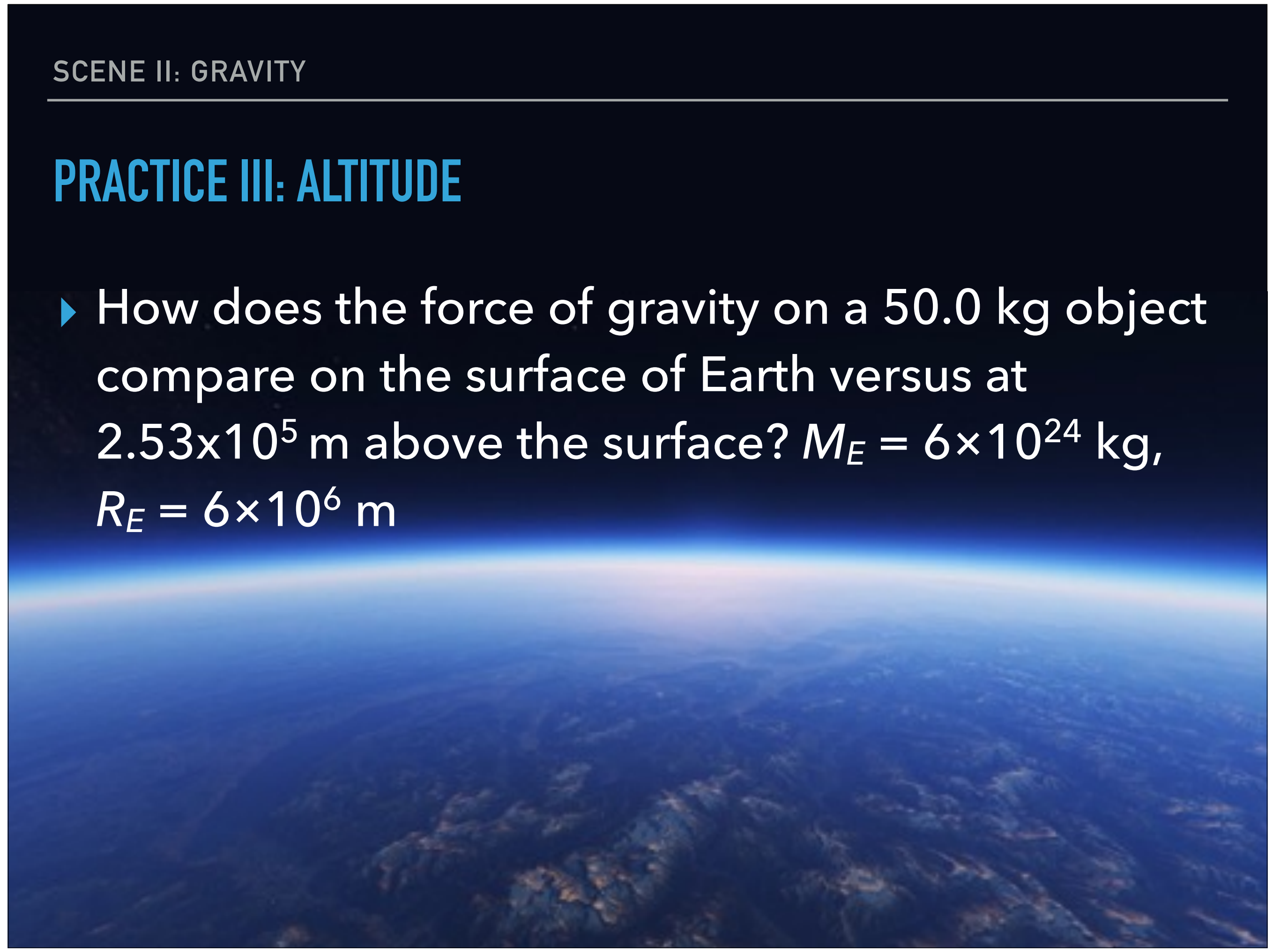
SANITY CHECK

- An apple on a tree feels 1N of force due to gravity
- If the tree were twice as tall, the force of gravity on the apple would then be:
    A. twice as strong
    B. half as strong
    C. a fourth as strong
    D. none of the above

SANITY CHECK

- An apple on a tree feels 1N of force due to gravity
- If the tree were twice as tall, the force of gravity on the apple would then be:
  - A. twice as strong
  - B. half as strong
  - C. a fourth as strong
  - D. none of the above

- Just because you doubled your height does *not* mean you doubled the distance from the center of the Earth



- Answer: $F_{g,surface} \approx 500$ N; $F_{g,above} \approx 500$ N (less than a 40 N difference)

- Astronauts in orbit are said to be “weightless,” but gravity is still acting on them. The astronauts are in perpetual free fall!
- This picture isn’t even from space. It’s a picture of a Zero G flight!

- Fire in ZERO-G!!
- https://www.youtube.com/watch?v=xdJwG_9kF8s

DOUBLE CHECK

Since the Moon is pulled to the Earth by gravitational attraction, why doesn't it crash into the Earth?

- Answer: The Moon has tangential velocity, so it tries to fall towards the Earth, but it misses

DOUBLE CHECK

If there is an attractive force between all objects, why do we not feel ourselves gravitating toward massive buildings in our vicinity?

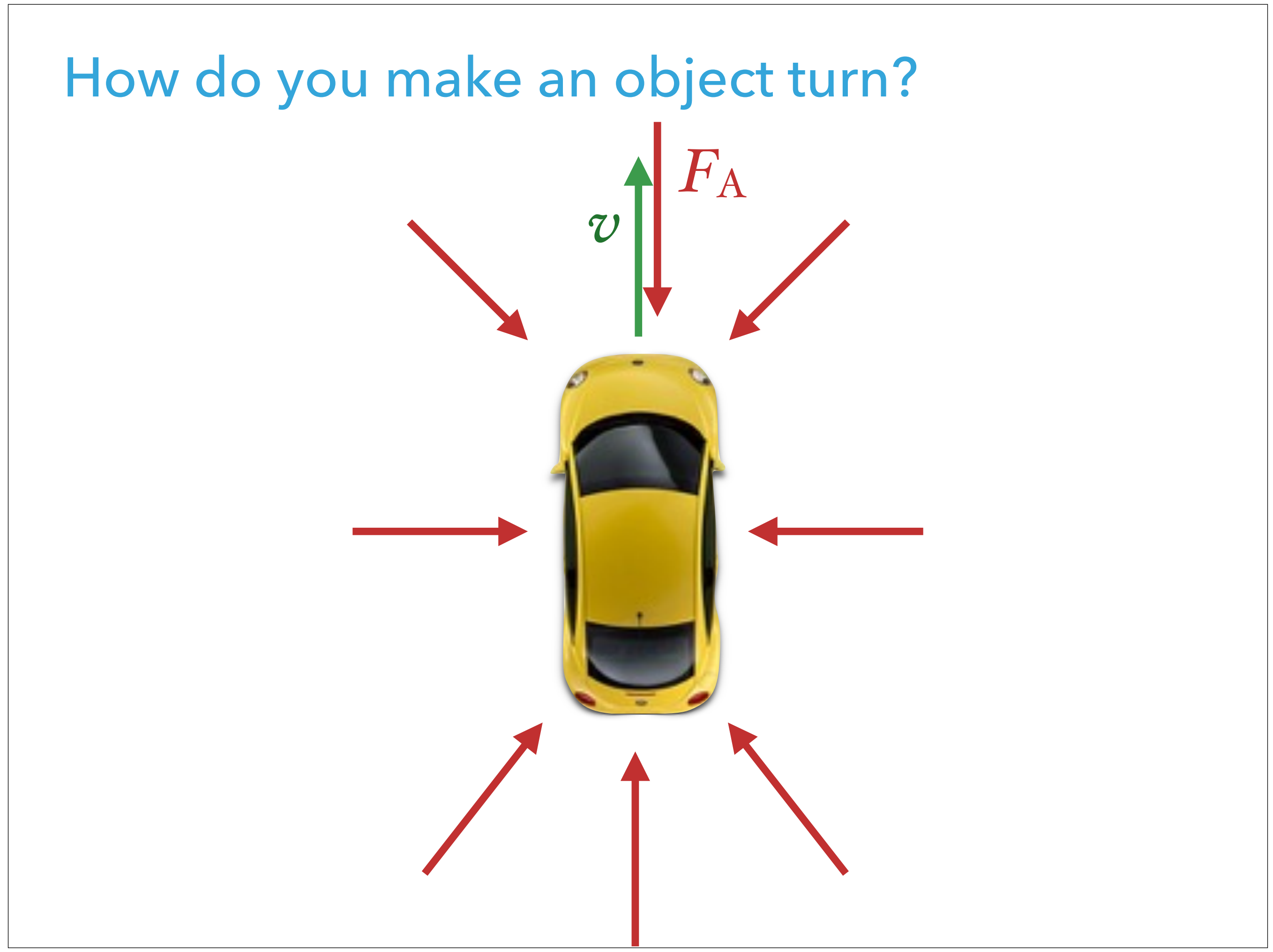
- Answer: The force of gravity is so weak, you wouldn't feel anything. Plus, you're getting pulled pretty much the same on all sides of yourself

DOUBLE CHECK

Which requires more fuel – a rocket going from from Earth to the Moon or a rocket coming from the Moon to Earth? Why?

- Answer: A rocket going from Earth to the Moon requires more fuel because it has to fight against a larger force of gravity

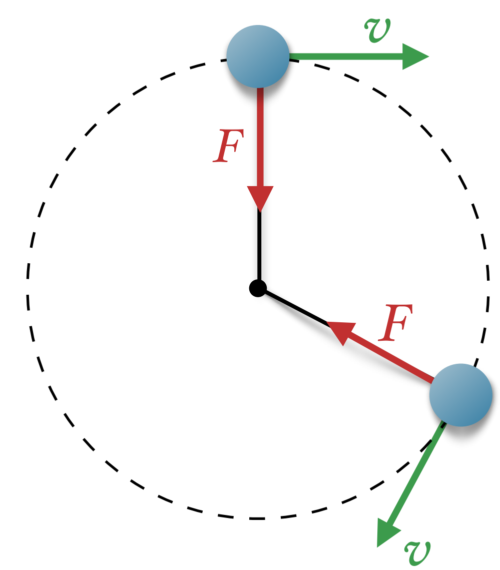
CIRCULAR MOTION



- 1st Law: An object in motion will tend to stay in motion at a constant speed in a *straight line* unless acted on by an external, unbalanced force.
- Ok, so we need an external, unbalanced force, but where should we apply it?

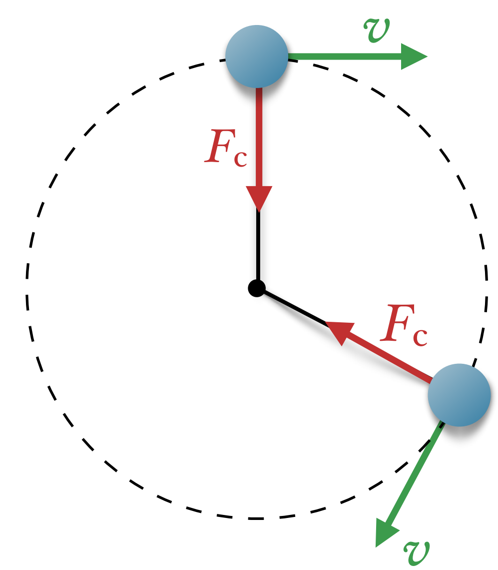
UNIFORM CIRCULAR MOTION

Which way must the force be acting to make the object move in a circle?



Centripetal Force – A force which points toward the center of rotation; literally means “center-seeking” force

- What forces act as centripetal forces?
  - ball on a string swung in a circle:
  - car rounding a bend:
  - orbit of planets:
  - rollercoaster car going around a loop:



TWO INGREDIENTS FOR CIRCULAR MOTION:

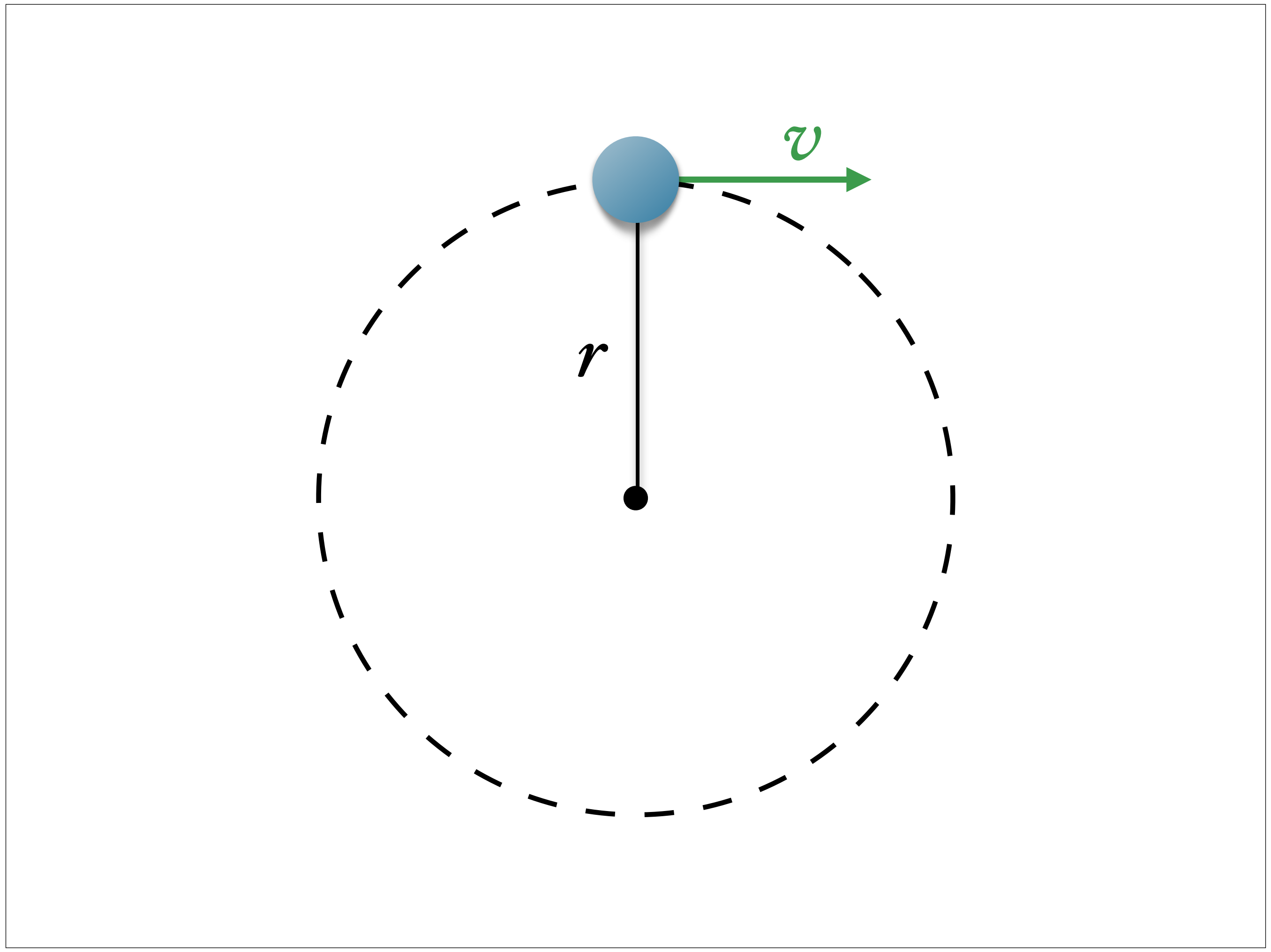
1. CENTRIPETAL FORCE
2. TANGENTIAL VELOCITY

CENTRIPETAL FORCE

$$F_c = \frac{mv^2}{r}$$

*the **centripetal force** is equal to the product of the object's **mass** & **velocity squared** divided by the **radius** of the circular path*

- Khan Academy Visual Proof: https://www.youtube.com/watch?v=TNX-Z6XR3gA



- Armed with only a ruler and stopwatch, calculate the swinging ball's speed

TANGENTIAL VELOCITY

$$v = \frac{2\pi r}{T}$$

*the **tangential velocity** is equal to the **circumference** of the circular path divided by the **period***

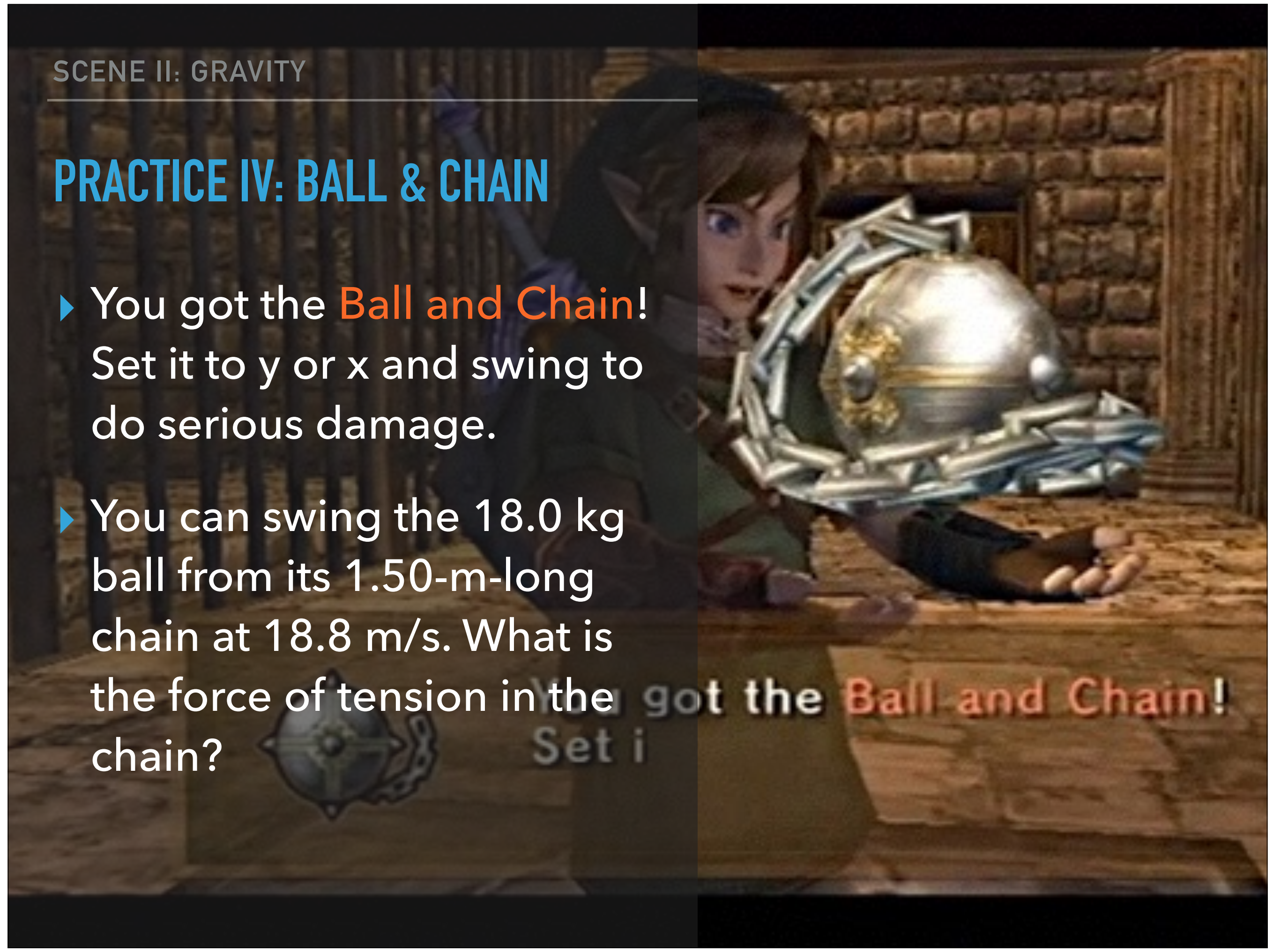
Period (T) – the time required to make one full revolution (measured in seconds)

Frequency (f) – the number of revolutions per second (measured in Hertz [Hz])

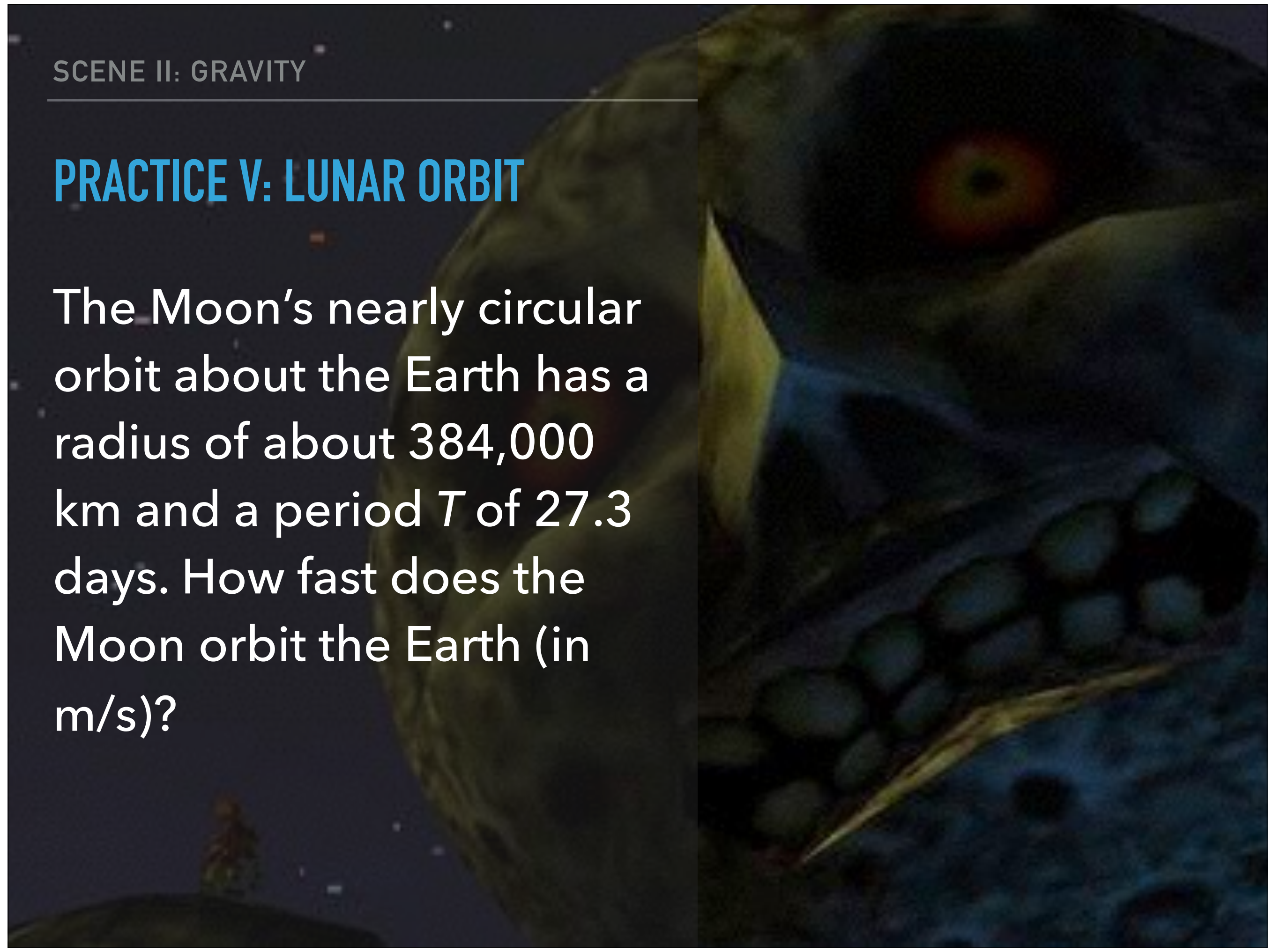
FREQUENCY & PERIOD

$$f = \frac{1}{T}$$

frequency *&* ***period*** *are* ***reciprocals*** *of each other*



- Answer: $F_T \approx 4000$ N



- Answer: $v \approx 1000$ m/s (~2000 mph)

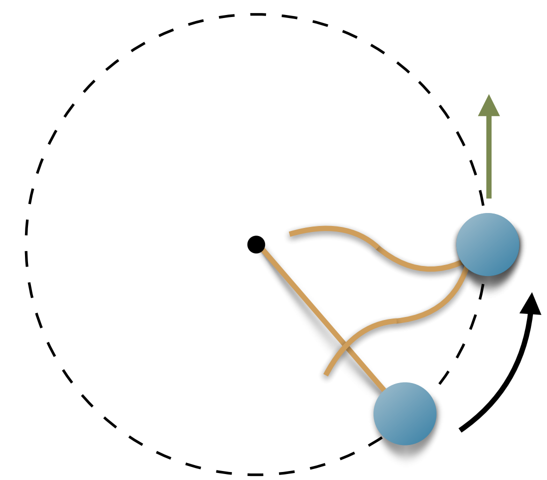
SANITY CHECK

- You're driving along in your car when you make a hard and quick left
- In what direction is the (net) force acting on your body?
  - *To the left!*

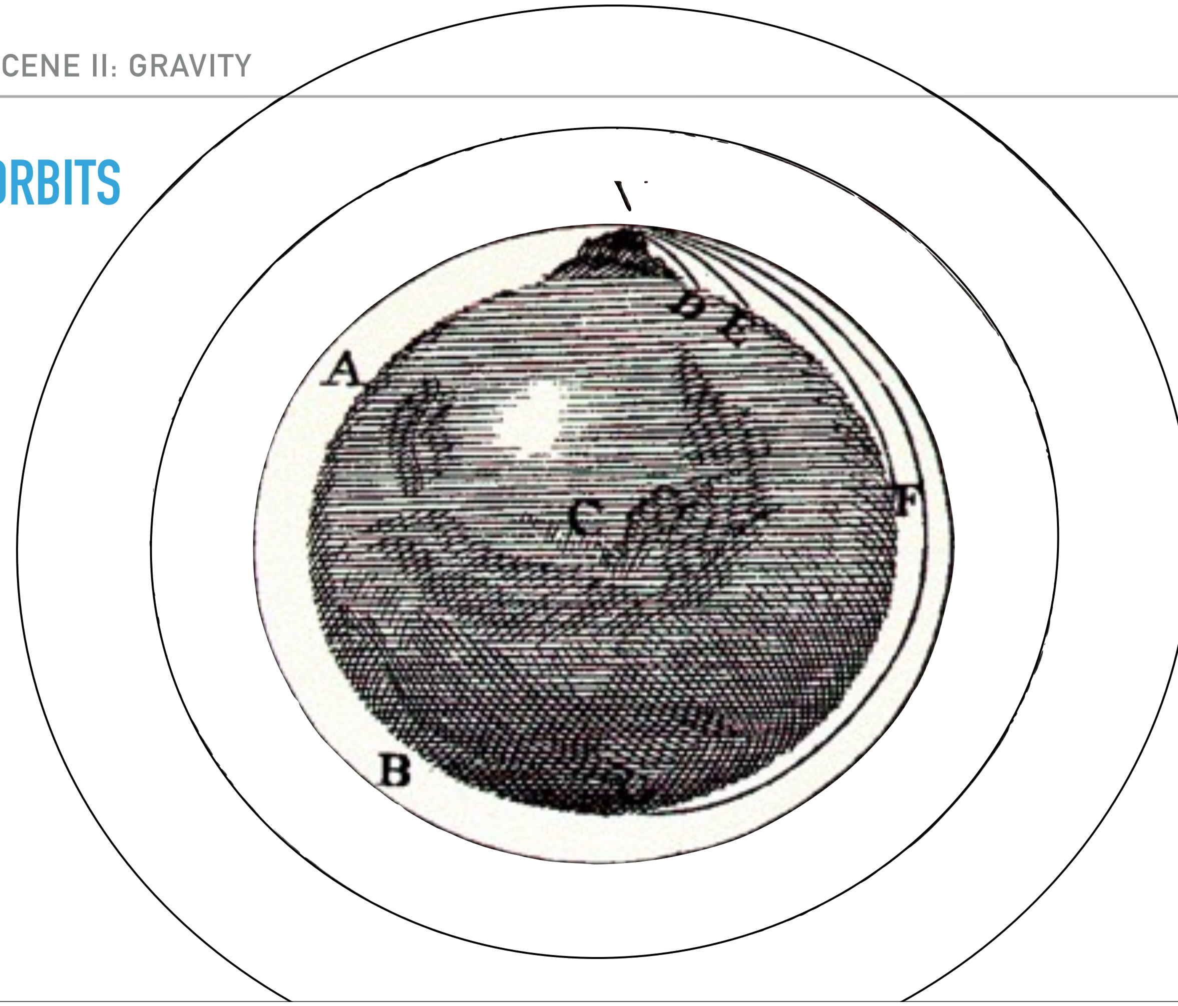
- But your body *feels* like it's being pushed to the right because your inertia resists changes to its motion
- The so-called *centrifugal* ("center fleeing") force is a fictitious force experienced because your reference frame (the car, in this case) is accelerating

SANITY CHECK

- A ball is swung in a horizontal circle and released as shown to the right. Which way will the ball travel once it's released?
  - *On a tangential path*



ORBITS



- Returning to Newton's thought experiment, what is the "magic speed" where the falling object begins to orbit?
- We can derive a relationship for orbital speed by treating gravity as a centripetal force

ORBITAL SPEED

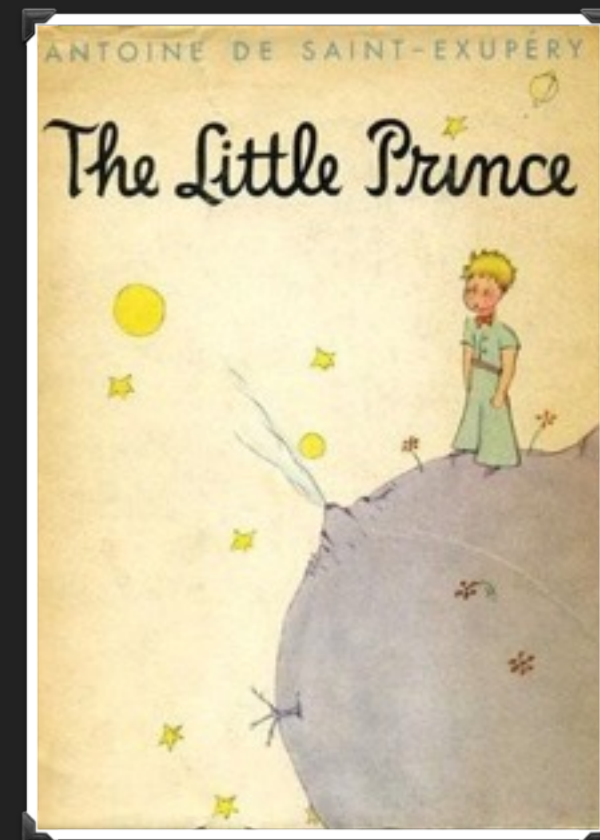
$$v_{orb} = \sqrt{\frac{GM}{r}}$$

*the **speed needed to begin orbiting** an object is equal to the square root of the product of the **gravitational constant** and the **mass** of the object being orbited divided by the **distance** between the centers of mass*

- Fire the cannonball slower than this, and eventually it will crash back into Earth
- Fire it faster, and the cannonball will orbit in an ellipse instead of a circle (though even in that case, this equation will still describe the *average* orbital speed)

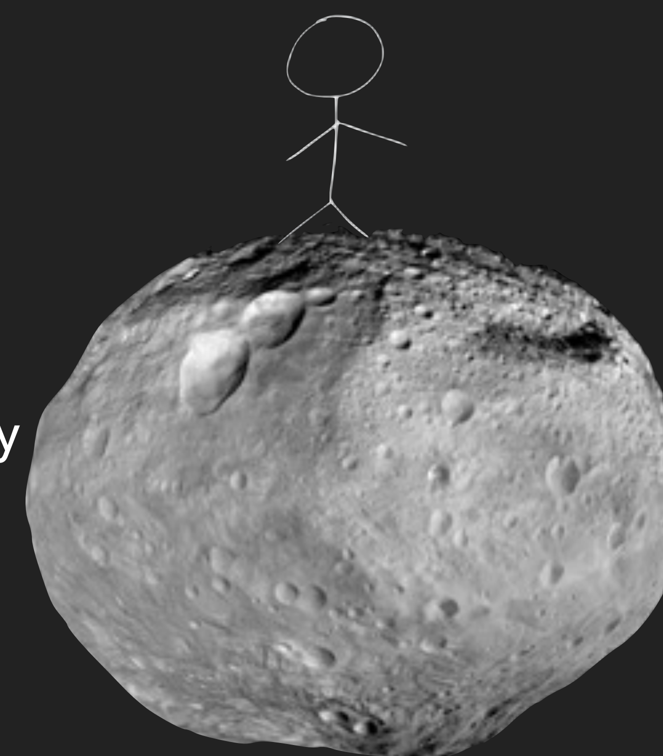
PRACTICE VI: LITTLE PLANET

If an asteroid was very small but supermassive, could you really live on it like the Little Prince?



PRACTICE VI: LITTLE PLANET

If the astroid has a radius of 1.75 m, what mass would it need to have in order to have the same acceleration due to gravity as Earth at its surface?



- Answer: $M \approx 4\times10$ kg (just under 600 million tons)
  - That's roughly equal to the combined mass of every human on Earth

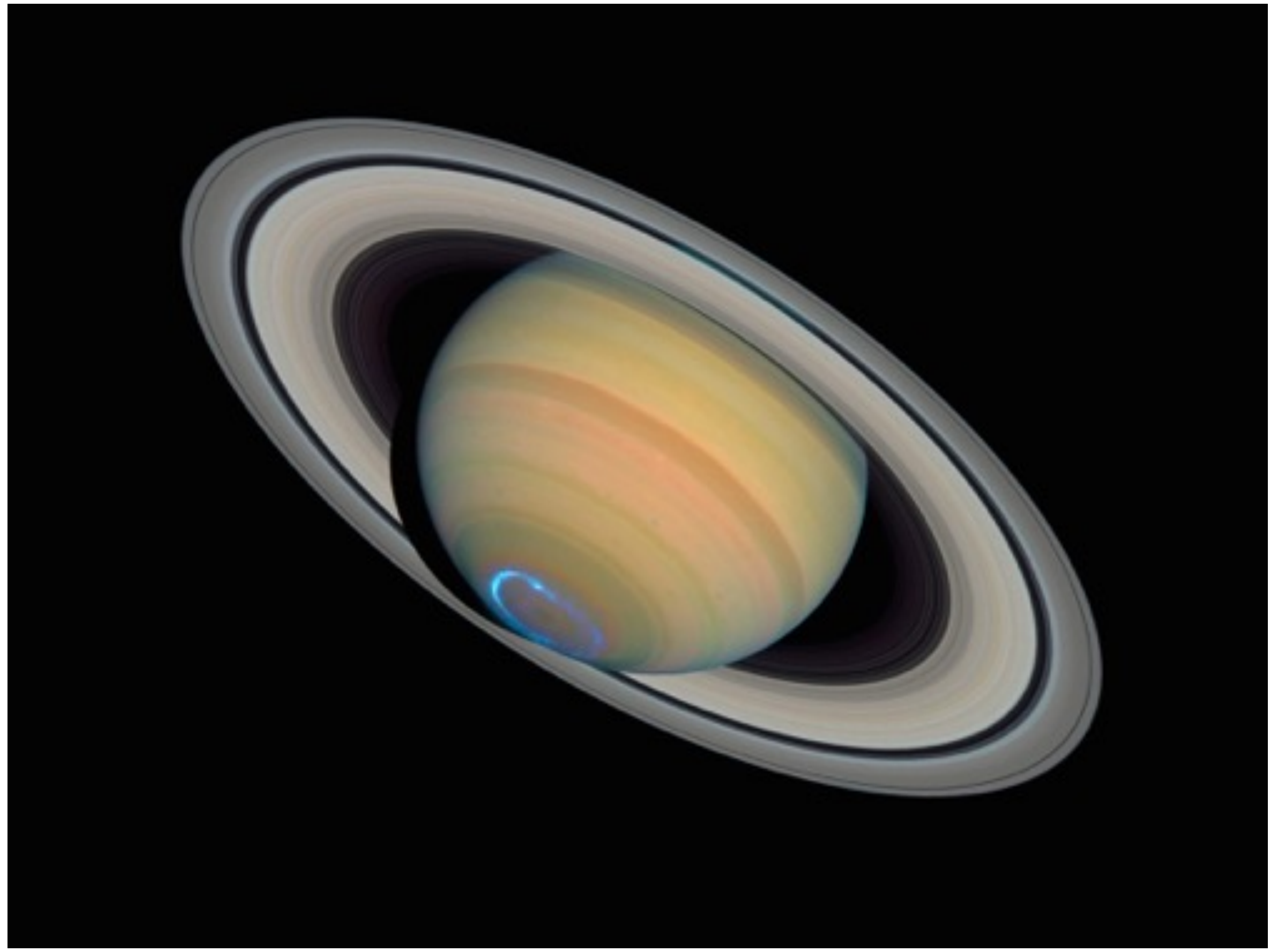
PRACTICE VI: LITTLE PLANET

What would be the difference between the force of gravity at your head vs. your feet?

Compare the force of gravity on 60 kg at the surface vs. 1.6 m (~5′ 3″) above the surface

- Answer: F_g (h = 0) ≈ 600 N; F_g (h = 1.6 m) ≈ 200 N
- It would feel like lying on a merry-go-round with your head near the center

Tidal Forces – where there’s a substantial difference in the force of gravity between different ends of a body



- Tidal forces are responsible for Saturn’s rings. A primordial moon drifted too close to Saturn and sheared apart by the strong tidal forces

- The same thing can happen to stars that drift too close to a blackhole

PRACTICE VI: LITTLE PLANET

Say your center of mass is 1.4 m above your feet. How fast would you need to run to start orbiting the asteroid?

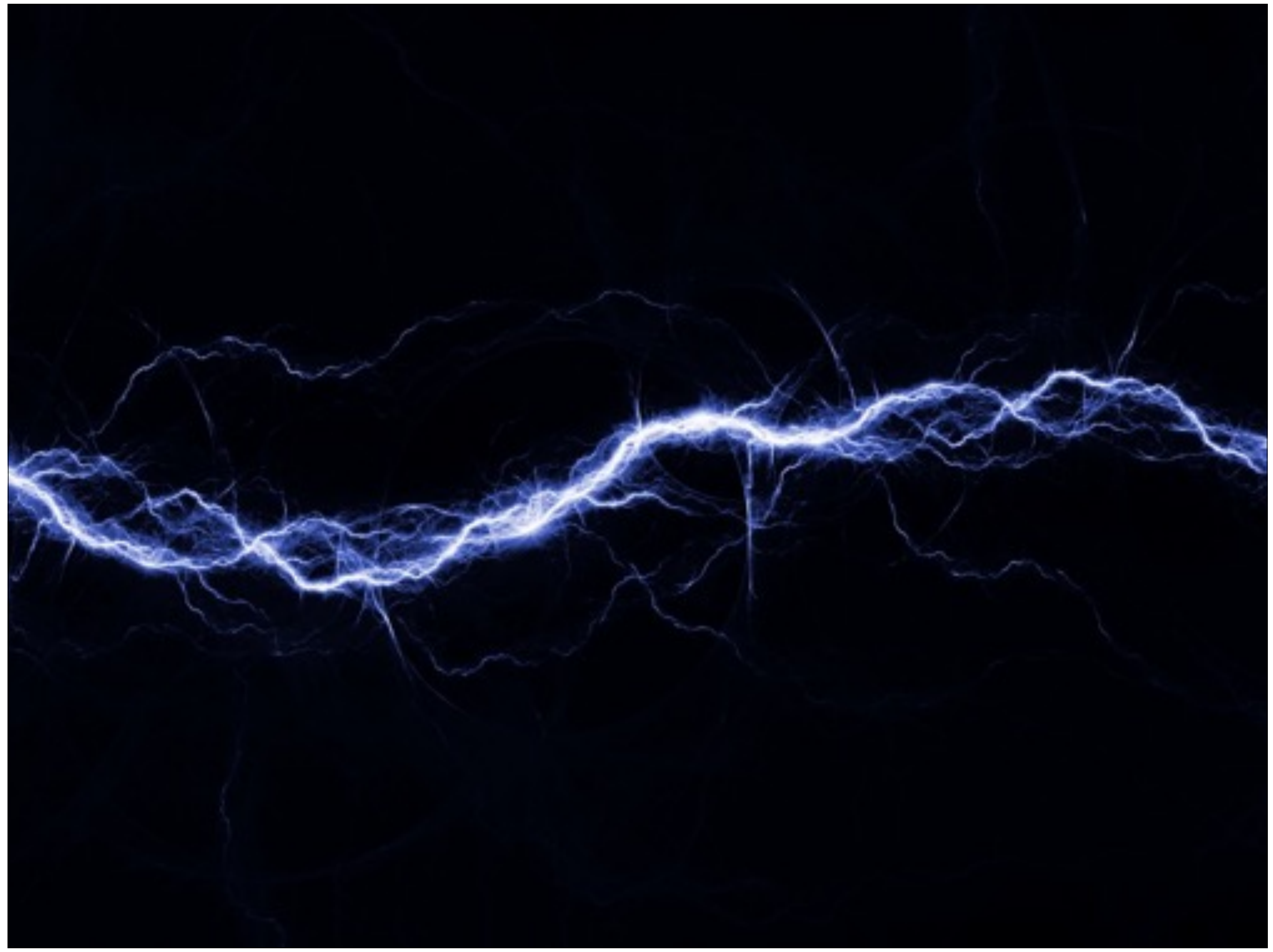
- Answer: $v_{orb} \approx 3$ m/s
  - That's typical jogging speed
  - However, this would be a *weird* orbit


THE PROPERTIES OF CHARGED
PARTICLES AND THEIR INTERACTIONS
SCENE III: ELECTRICITY

- Our first exploration of electricity was through investigating static

- The ancient Greeks discovered that if you rub an amber rod with a piece of cloth, the amber attracts small pieces of leaves or dust
- The word electricity comes from the Greek word *elektron*, meaning “amber”

- English physician, physicist and natural philosopher
- Set out to find which substances, other than amber, which on rubbing produced a similar effect
  - Found that a number of gems could be electrified, including diamond, sapphire, amethyst, opal, and even ordinary rock crystals
  - Other substances, particularly metals, could not be electrified by these means



- Eventually, electricity came to be thought of as a fluid, so when a substance like amber was electrified, it was considered to have gained electric fluid

CA. 1602 - 1686

OTTO VON GUERICKE

- German scientist, inventor, and politician
- Before electric forces could be studied easily, the fluid had to be concentrated into sizable quantities, so an “electric” that was cheap and available in sizable quantities had to be found
- In the 1660s, Von Guericke found such a material in sulfur and built a sphere of the stuff that he then could crank and charge by friction

VON GUERICKE'S DISCOVERIES

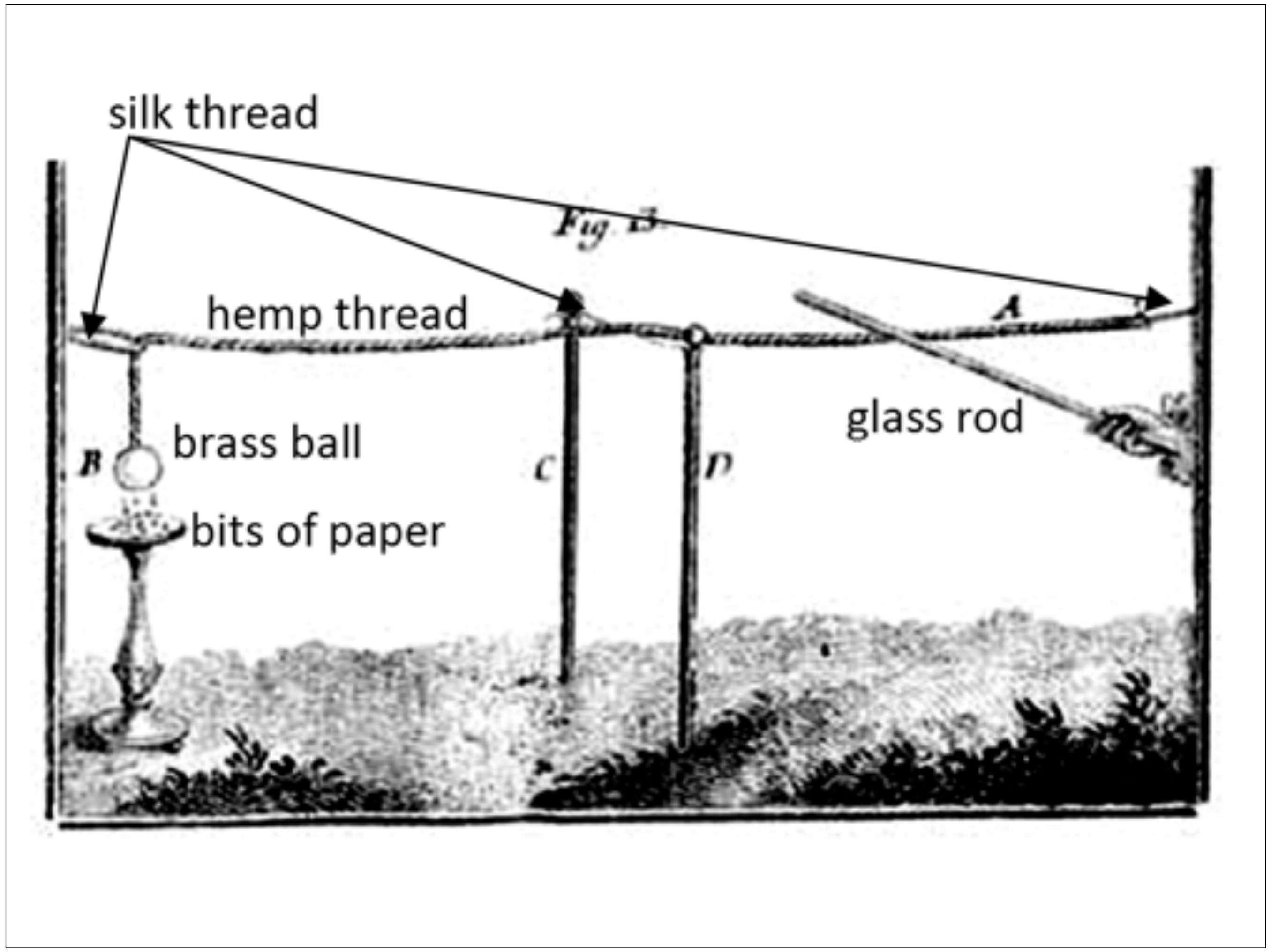
1. Like magnets, electrics display electrostatic repulsion as well as attraction
2. A substance brought near the electrified sulfur itself exhibited temporary electrification

- This "temporary electrification" is analogous to a piece of iron held near a magnet can become temporary magnetized. Thus, there is *electrostatic induction* as well as magnetic induction

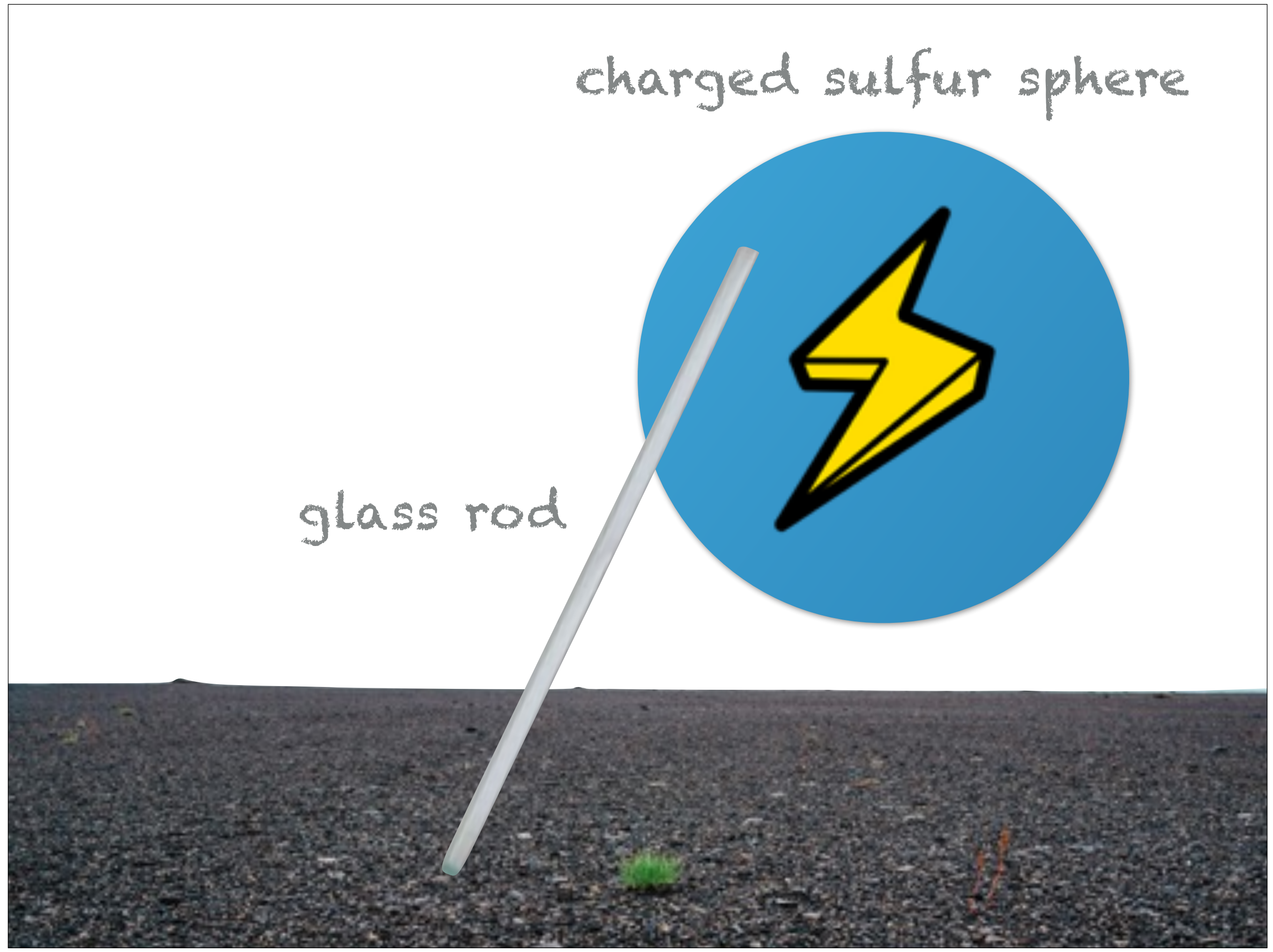
CA. 1666 - 1736

STEPHEN GRAY

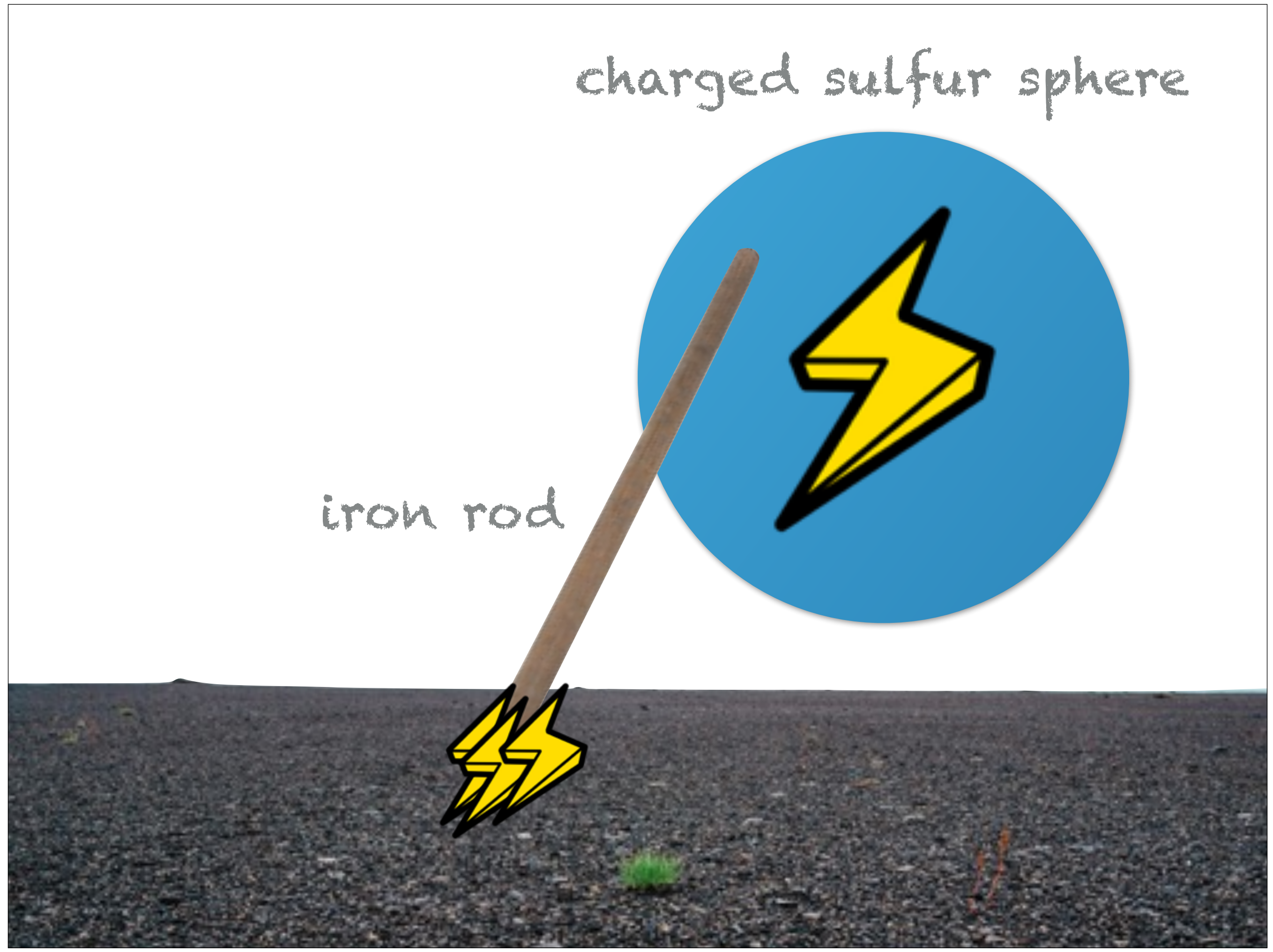
- English astronomer and electrician



- After rubbing the glass rod and touching it to hemp rope, the brass ball on the opposite end would itself become electrified
- So, it would seem, electricity has a tendency to spread itself throughout the substance — through the hemp rope and into the brass ball. Electricity *moves*



- Electricity doesn’t spread through all materials with equal ease, however
- “Electrics,” like the glass rod, for example, could be used to connect the charged sulfur sphere to ground, but nothing would happen



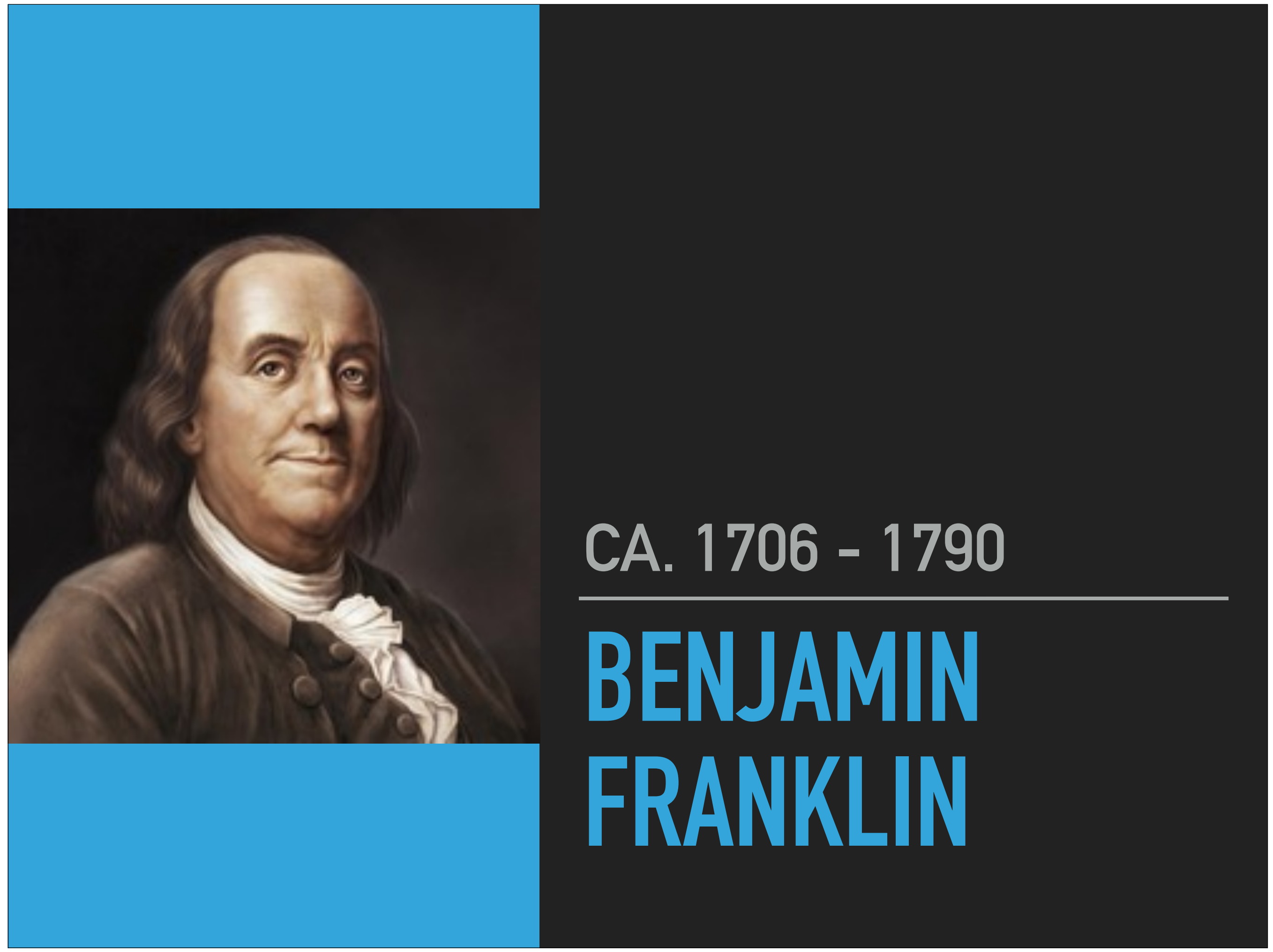
- When, however, a “nonelectric,” like iron, was used to connect the charged sphere to ground, the sphere almost immediately lost all its charge — was *discharged* — and all the electricity drained into the earth, where it spread so thinly it could no longer be detected
- This seemed to explain why metals couldn’t be electrified by rubbing (as quickly as charge was placed on the metal, it would discharge into whatever else the metal was touching)

Conductors – materials that allow the passage of electricity with great readiness

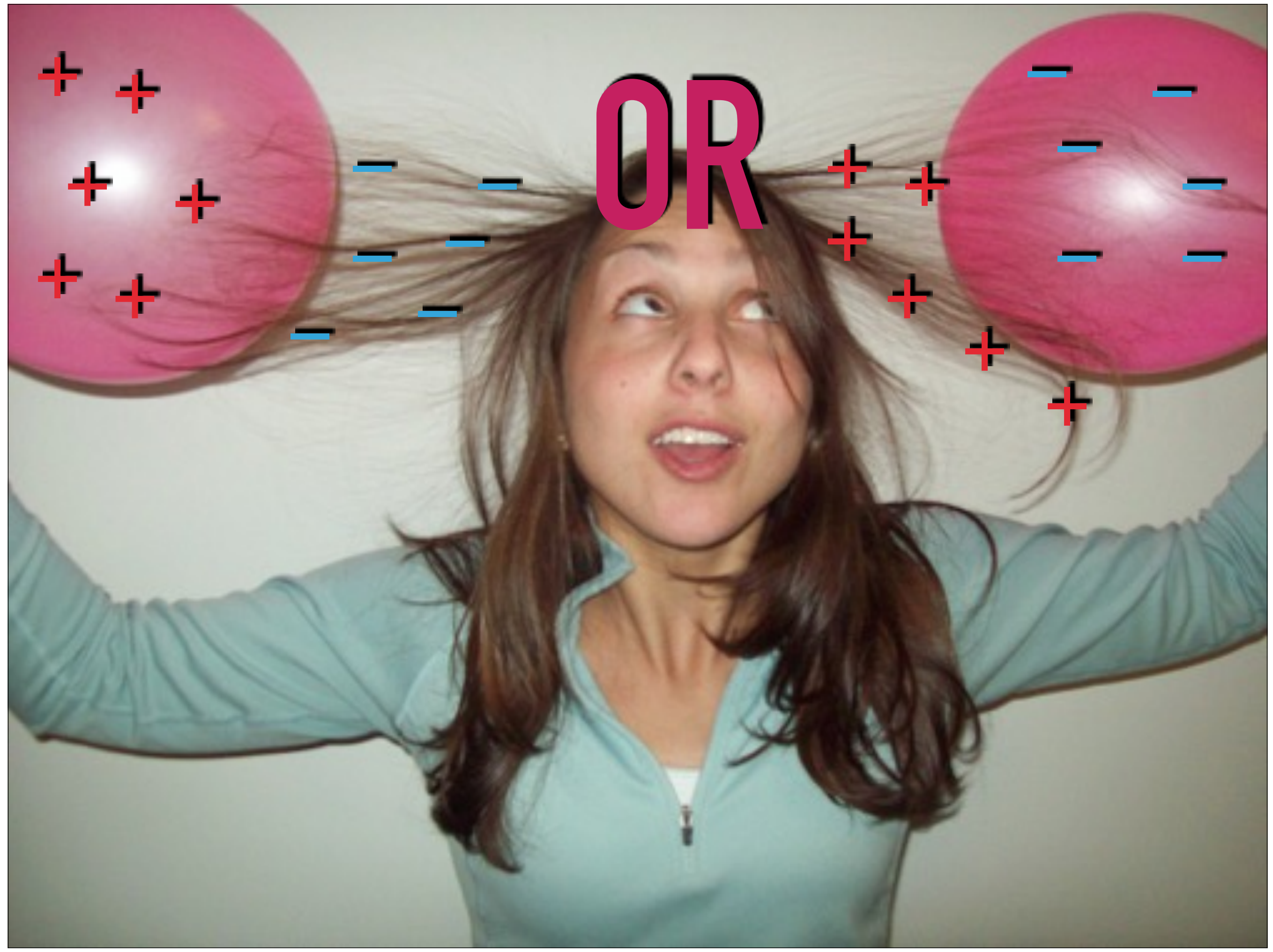
Insulators – materials that resist the flow of electricity

- As a result of Gray's work, matter came to be divided into two categories: *electrical conductors* and *electrical insulators*
  - Metals are the best examples of electrical conductors
  - Other materials like amber, glass, sulfur, and rubber (the materials easily electrified through friction) represent the insulators

- French chemist and superintendent of the Jardin du Roi
- Deduced that there were two types of electric fluid, which he called “vitreous electricity” (from a Latin word for glass) and “resinous electricity”
  - As in the case of the north and south poles of magnets, like repelled and unlikes attract



- English/American author, printer, political theorist, politician, freemason, postmaster, scientist, inventor, civic activist, statesman, and diplomat
- In the 1740s, he conducted experiments which demonstrated that a charge of “vitreous electricity” could neutralize a charge of “resinous electricity,” leaving no charge at all behind
  - The two types of electricity were not merely different; they were opposites
- Franklin’s theory: there’s only one fluid — when that fluid is present in normal amounts, the object is neutral; if there’s an excess of the fluid, Franklin considered the object *positively charged*; and if there’s a deficit, he considered it *negatively charged*



- Differentiating between magnetic poles is easy: does a particular pole point north or south? Done.
- No such standard for electricity. There is no absolute difference in behavior between “vitreous” and “resinous” electricity — the two forms differ only in reference to each other
- Franklin, forced to guess, decided that the glass rod when rubbed gained electric fluid and was thus positively charged, while the resin rod lost electric fluid and was thus negatively charge.
    - The charge of anything else would then be determined in reference to that standard

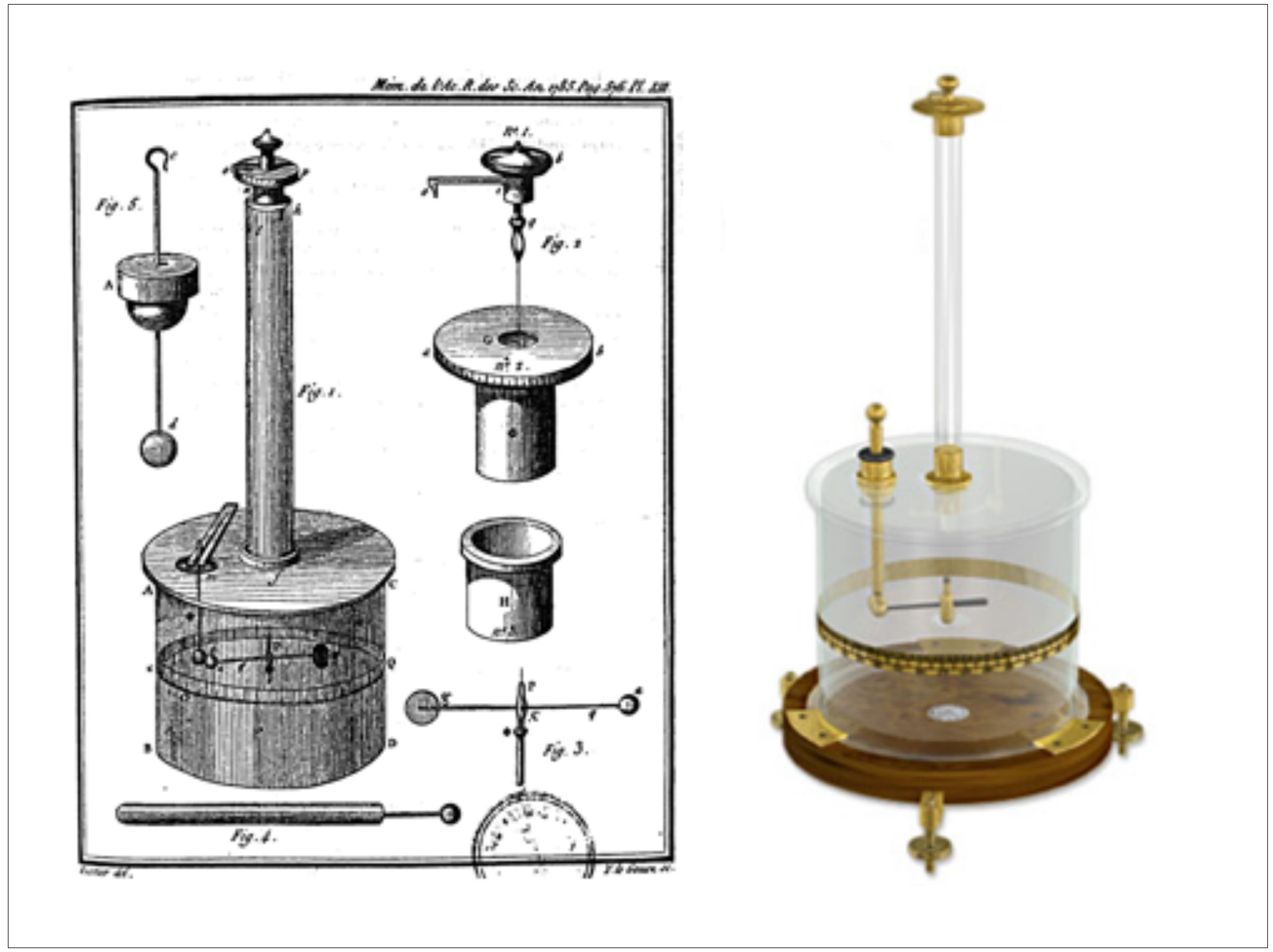
CHARGE IS CONSERVED

- Franklin made an important assumption: electric charge can neither be created nor destroyed. Any net charge gained must come from somewhere else, and any net charge lost could alway be found in another place

CA. 1736 - 1806

CHARLES-AUGUSTIN DE COULOMB

- French physicist who measured how the electrostatic force scaled with charge and with distance (he’d subsequently do the same for magnetism)



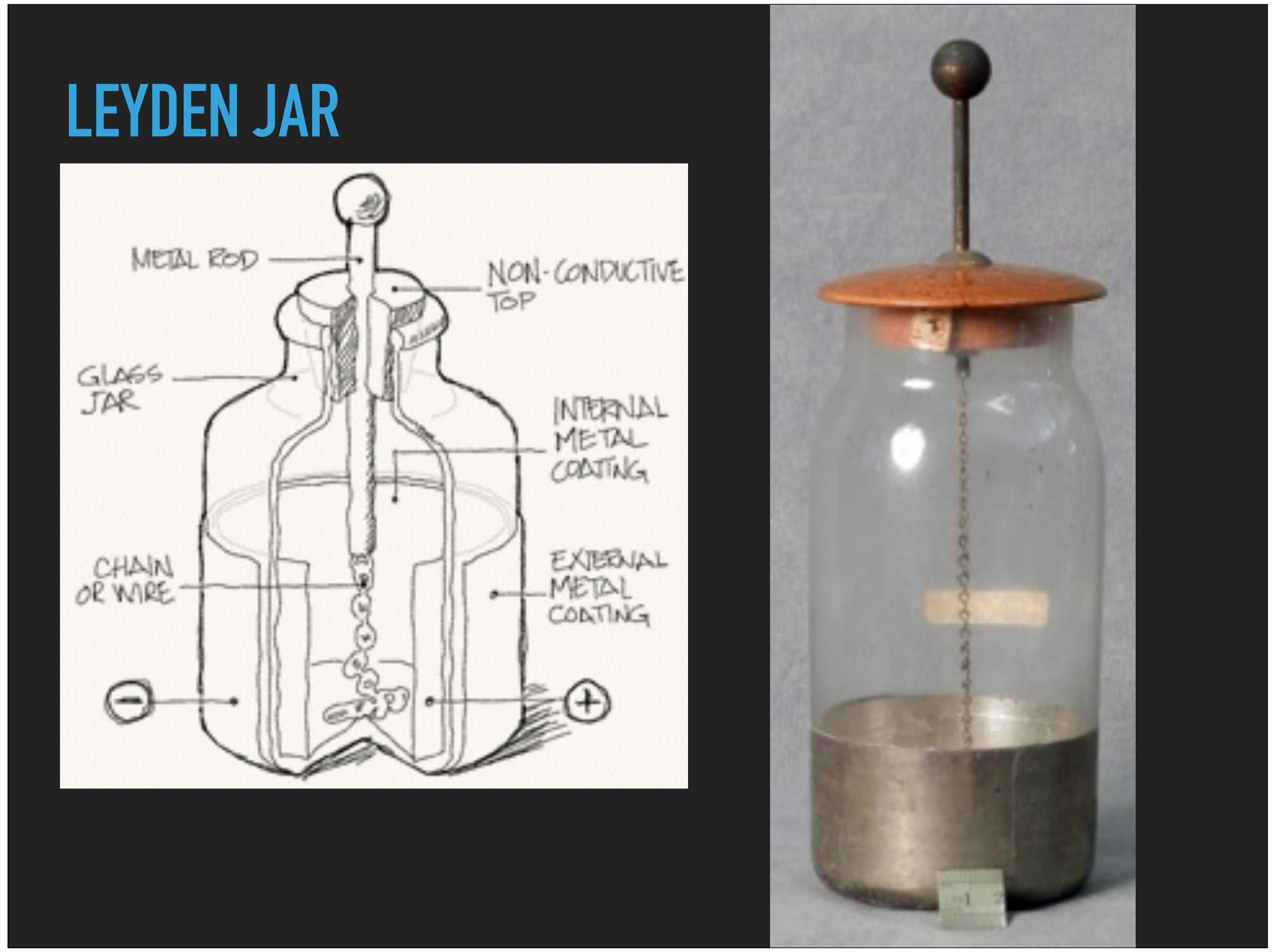
- Coulomb used a torsion balance to measure the electrostatic force in much the same way Cavendish had with the gravitational force

ELECTROSTATIC FORCE & INVERSE SQUARE LAW

$$F_e \propto \frac{q_1 q_2}{r^2}$$

*the **electrostatic force** is proportional to the product of the **charges** & inversely proportional to the **distance squared***

- Coulomb’s experiments demonstrated that the electrostatic force, like gravity, obeys the inverse square law



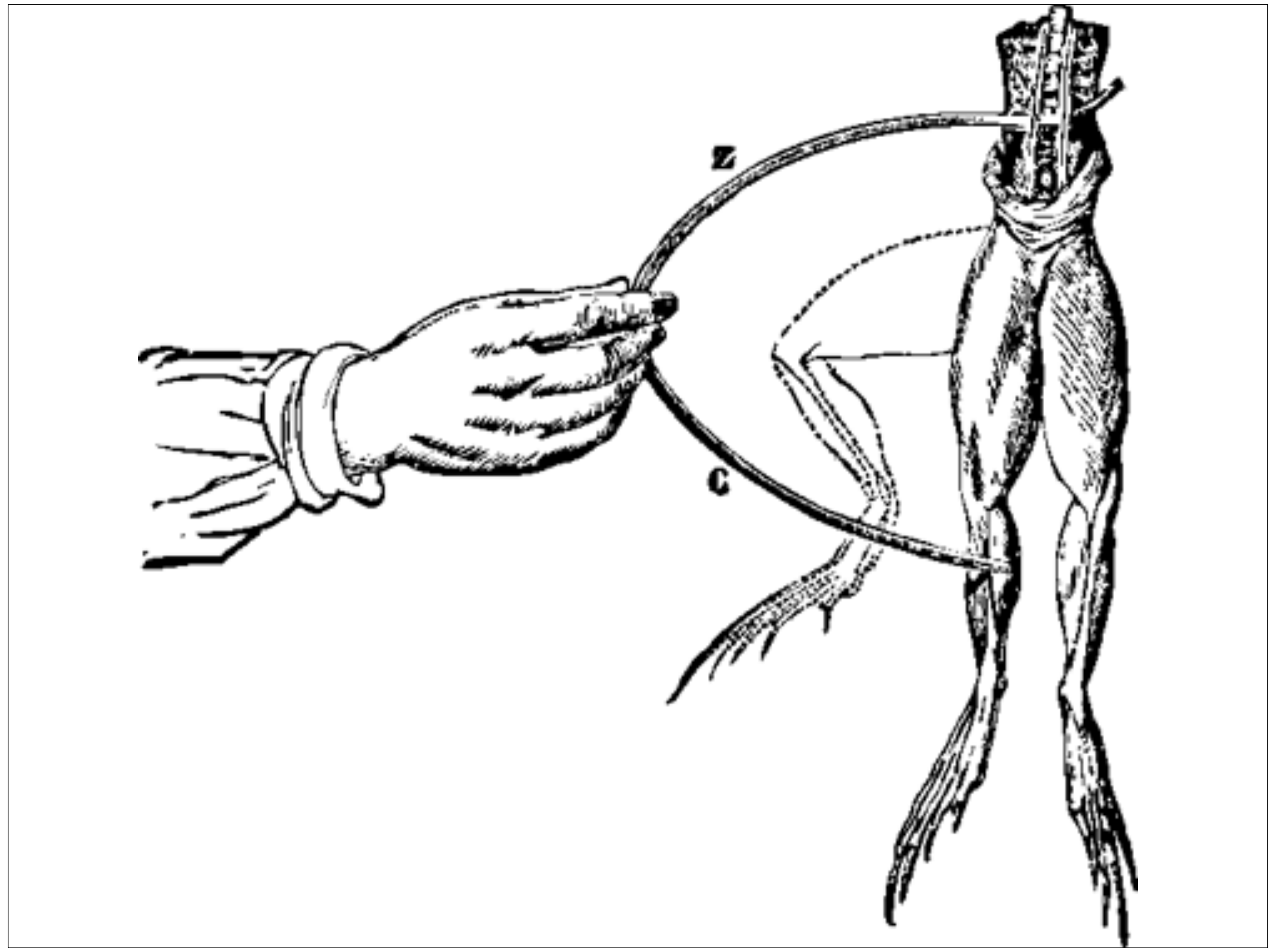
- At this point, the amount of charge scientists were able to store up was very small since the more charge you put on an object, the harder it gets to keep putting on charge
- The Leyden jar was invented in 1745 as a means of storing unprecedented amounts of charge
    - This was also the first time we discovered we could be shocked by electricity

- Franklin noticed the similarities between the bolts that leapt off the Leyden jar and bolts of lightning
- He tied a metal rod to a kite and a metal key to his end and flew the kite into a thunderstorm
    - The fibers of the kite chord stood on end, like static-y hair
    - When he brought his hand close to the key, a bolt leapt across, just like with the Leyden jar
    - He also charged a Leyden jar and reproduced all the same effects as with previous methods of charging
- It was clear that lightning was electricity — no different in the heavens as on earth
- Franklin used this knowledge to invent the lightning rod to shield buildings from the devastating effects of a lightning strike

CA. 1737 - 1798

LUIGI GALVANI

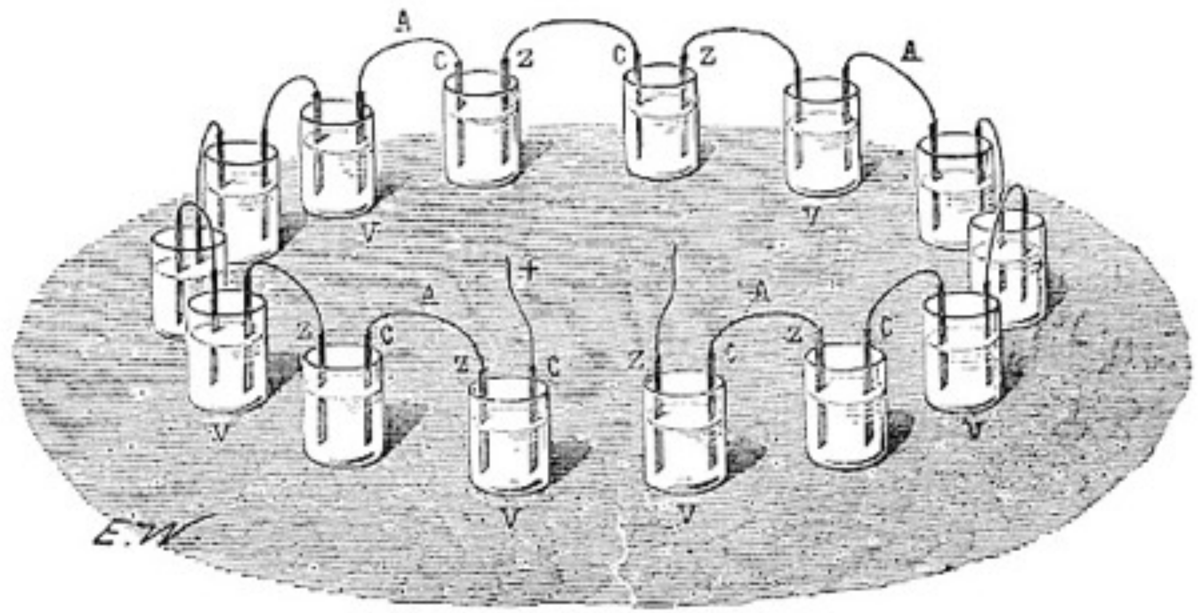
- Italian physician, physicist, biologist and philosopher
- It had previously been observed that an electric spark from a Leyden jar could cause the muscles in a dissected frog to twitch



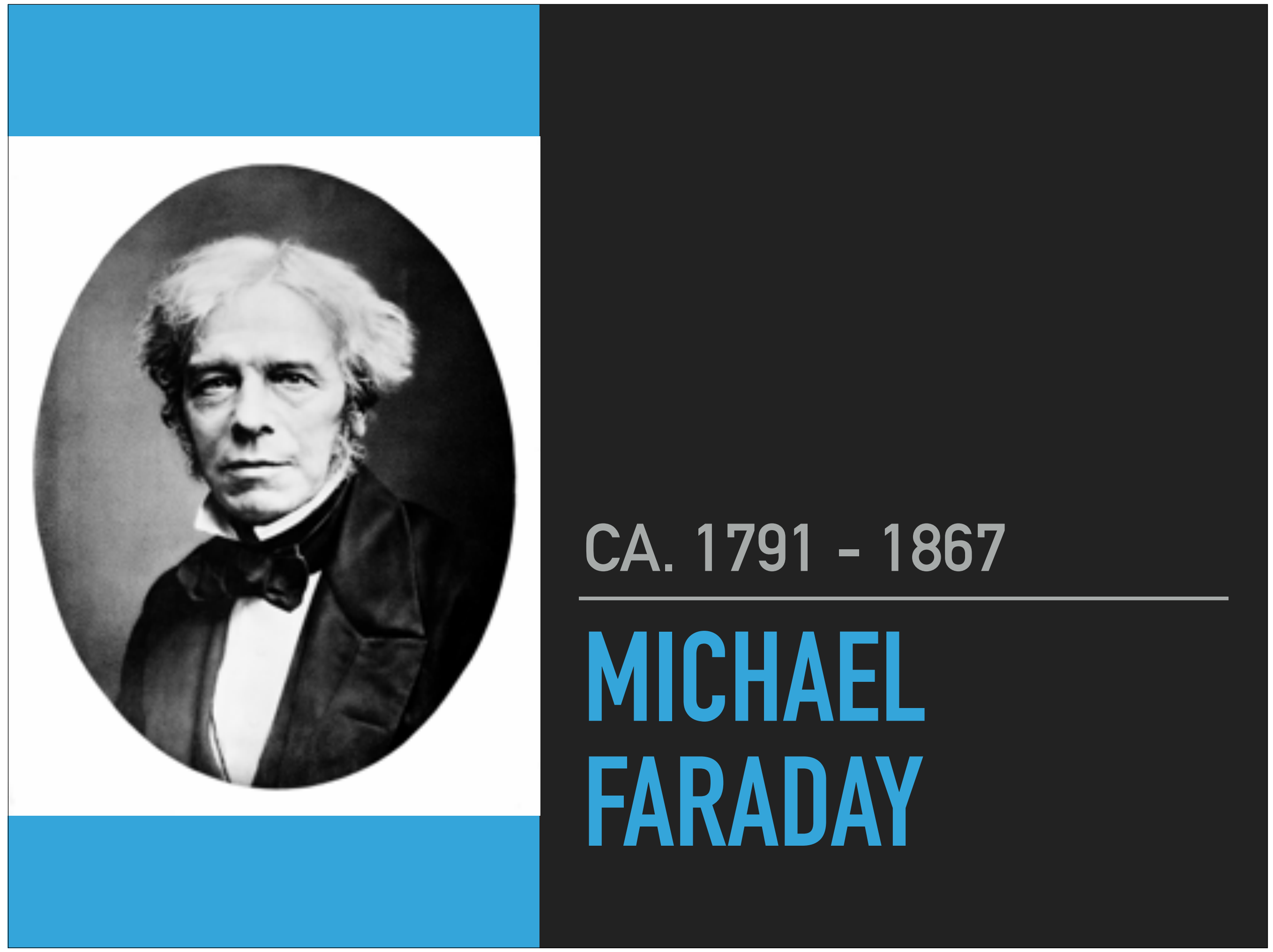
- Galvani discovered that all that was needed to produce this same effect was to make simultaneous contact with the muscle and two dissimilar metals
    - Galvani believed the source of the electricity was some inherent “animal electricity”

- Italian physicist, chemist, and a pioneer of electricity and power
- He suspected that the origin of electric charge might lie in the junction of the two metals rather than in the muscle
- He studied combinations of dissimilar metals connected, not by muscle tissue but by simple solutions

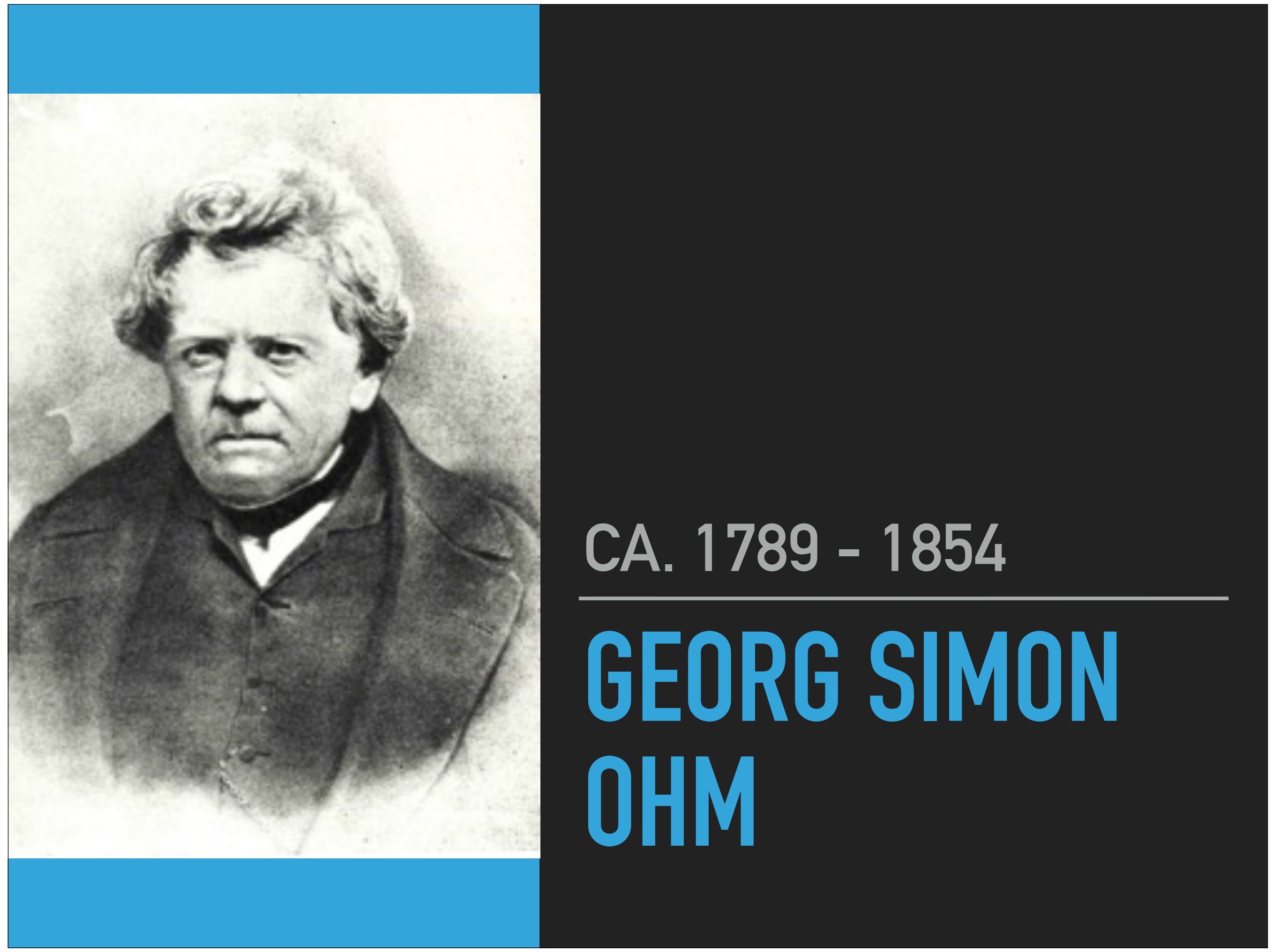
CROWN OF CUPS



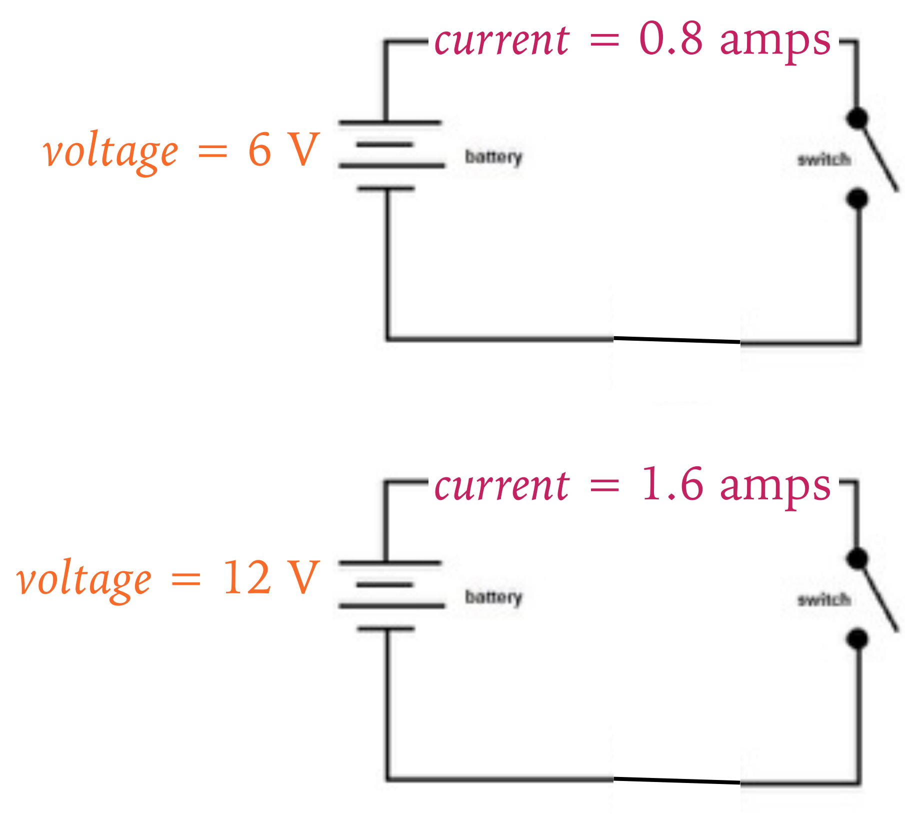
- Each cup was half filled with salt water, and a rod of copper and rod of zinc were dipped in the bath and connected from one cup to the next
- The “crown of cups” could be used as a source of electricity, which was shown to originate in the metals and not in animal tissue
- Moreover, the electricity was produced continuously and could be drawn off as a continuous flow
  - Volta invented the first battery — the first reliable source of continuous electrical energy
  - However, it took another full century to understand *why* it worked



- English scientist who contributed to the study of electromagnetism and electrochemistry
- Challenged us to think of electricity and magnetism in terms of fields
- Discovered the fundamental relationship that connects electricity and magnetism and later used this knowledge to develop the first electric motor and generator



- German physicist and mathematician
- Sought a relationship between the voltage supplied by the battery and the rate at which the current of electric charge flowed between two points



- He found that the amount of current flowing through the wire was proportional to voltage applied to it. So, for example, doubling the voltage always doubled the amount current

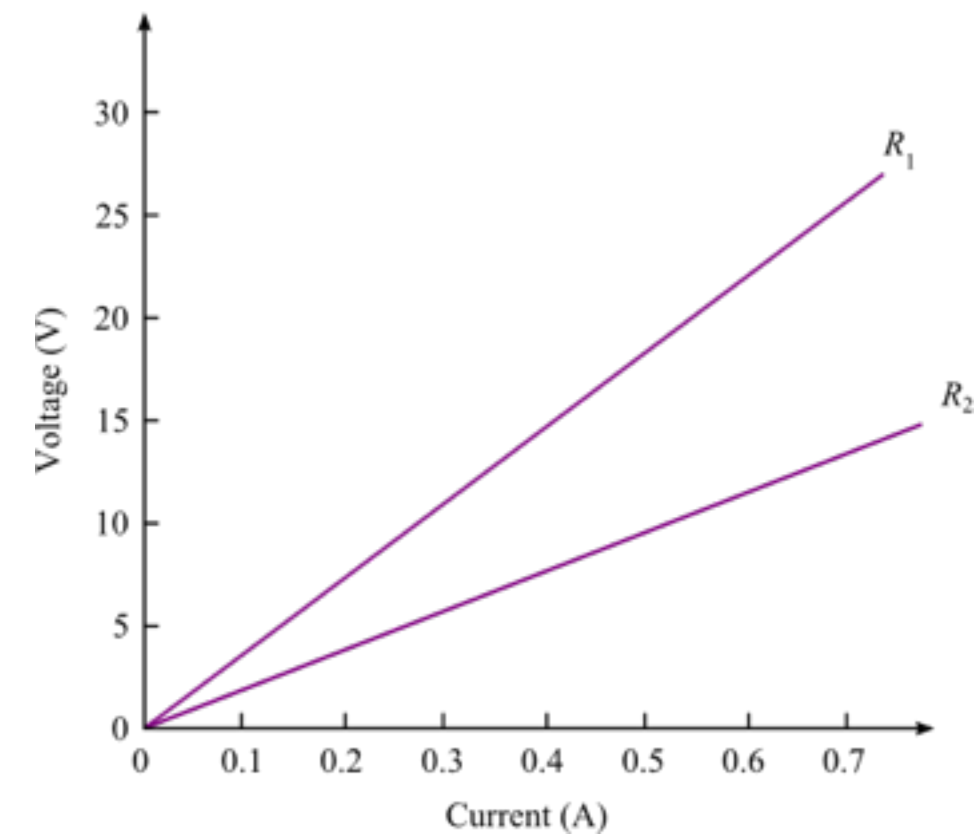
$$I \propto V$$

*the **electric current** flowing through an object is to proportional the **voltage** difference across that object*

Electric Current – the rate of flow of *electric charge*, i.e. how much charge moves past per second (measured in amps [A])

Voltage – the amount of *energy* supplied per charge (measured in volts [V])

- Ohm also tested what effect the wire itself had on the flow of current by changing qualities of the wire like material, length, and thickness and found that these, too, changed the current



- These two lines might represent voltage vs current in two wires of different material, different length, or different width
- Ohm dubbed the slope of these lines the wire's *resistance* to the flow of electric current

OHM'S LAW

$$V = IR$$

voltage** is equal to the product of **current** and **resistance

- Really, I think it should be written as $I = V/R$, because that isolates your dependents (current) on the left side of the equal sign and your independents (voltage and resistance) on the right

RESISTANCE

$$R \propto L/A$$

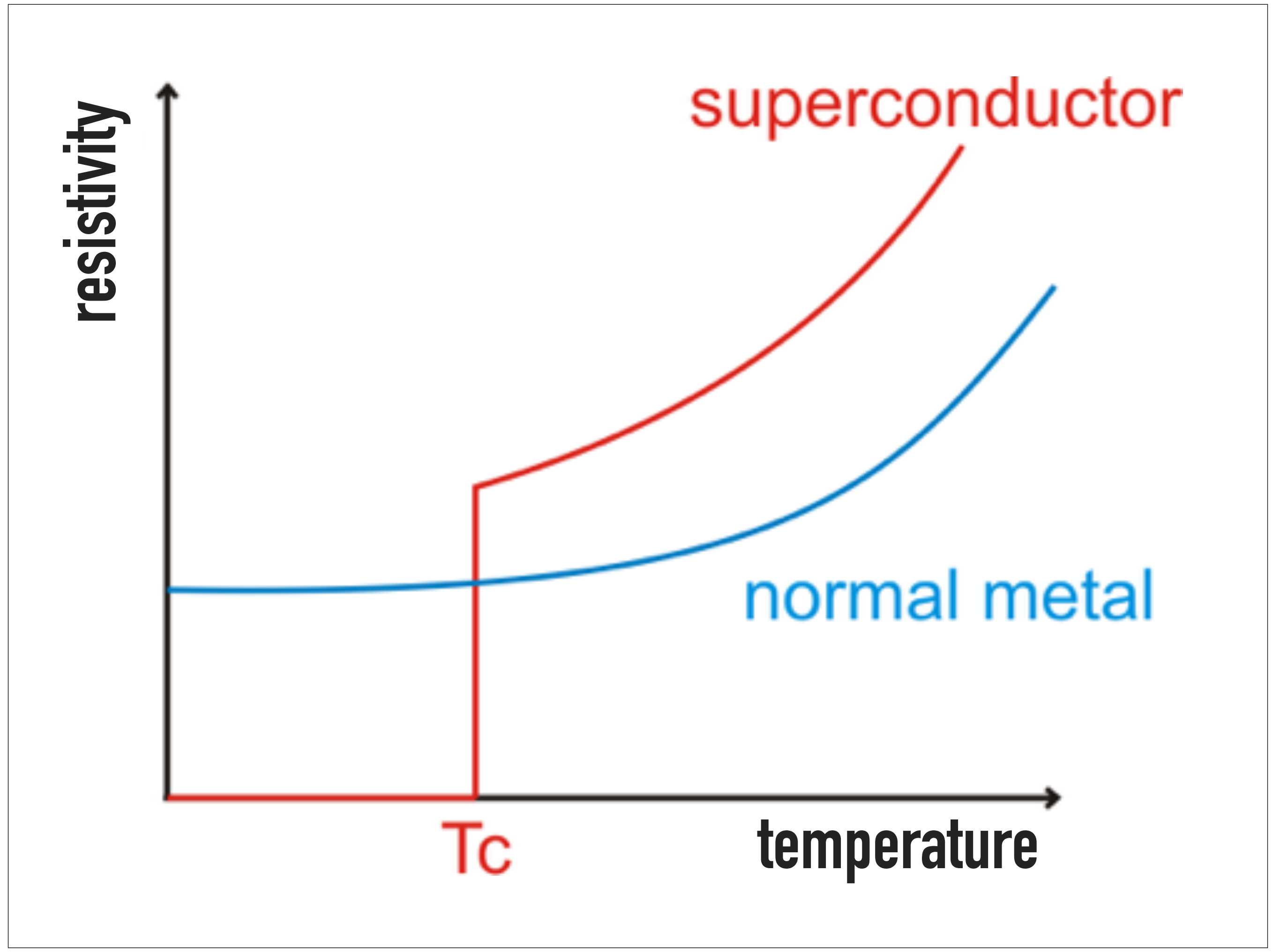
*the **electrical resistance** of a material is proportional to the **length** and inversely proportional to the **cross-sectional area** of the material that the current must pass through*

- Resistance is also dependent on what kind of material is being considered. I.e. the better a conductor the material is, the lower the resistance
- It also depends on temperature — the colder it is, the lower the resistance

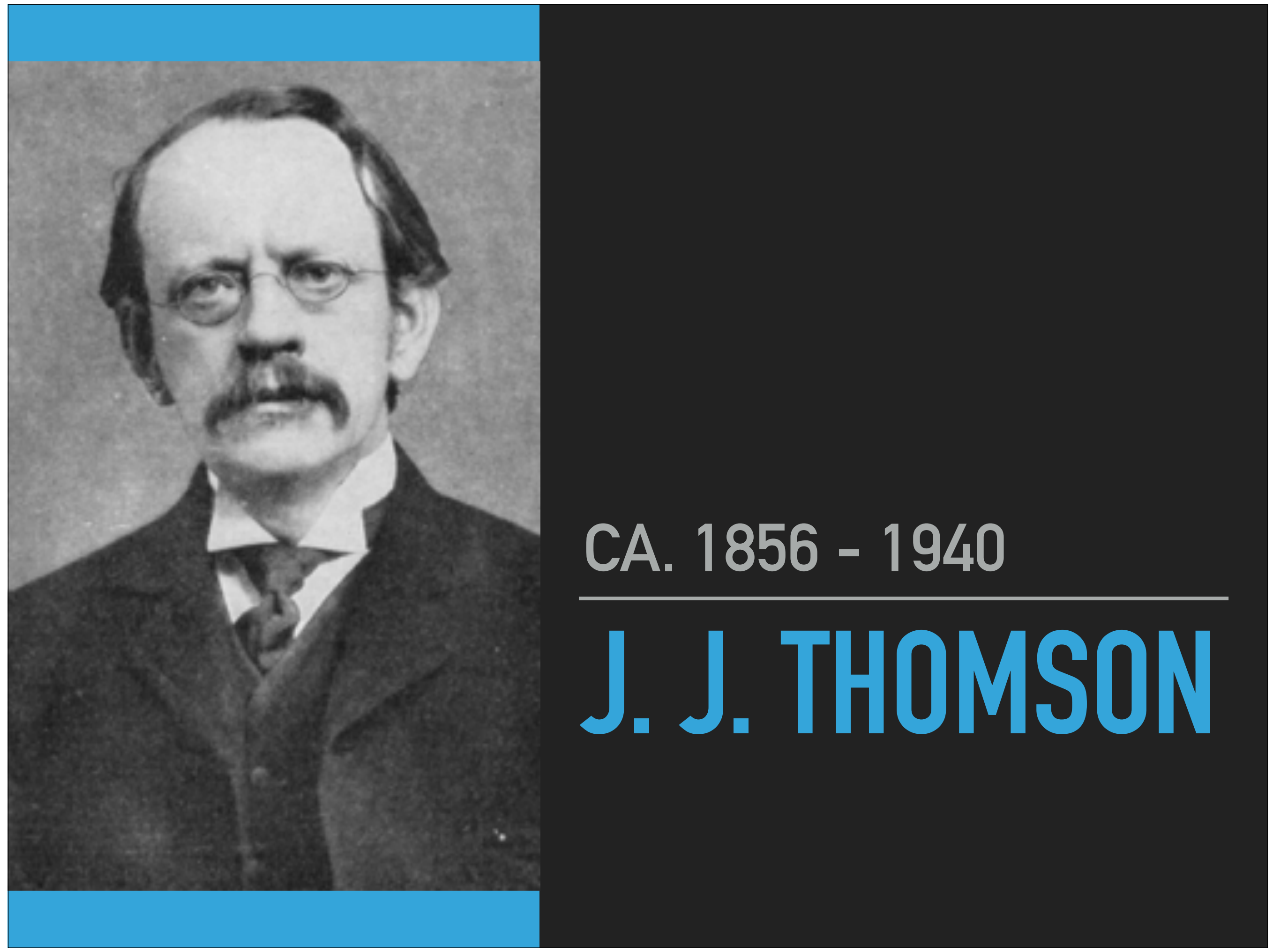
CA. 1853 - 1926

HEIKE KAMERLINGH-ONNES

- Dutch physicist and Nobel laureate
- Managed to liquify helium in 1908 (which, of all substances, has the lowest liquefaction point, 4.2 K) making low temperature physics research possible for the first time
- In 1911, he made a surprising discovery: he found the resistance of mercury grew smaller and smaller in expected fashion as temperature decreased, but the resistance dropped suddenly to exactly zero at or below temperatures of 4.16 K



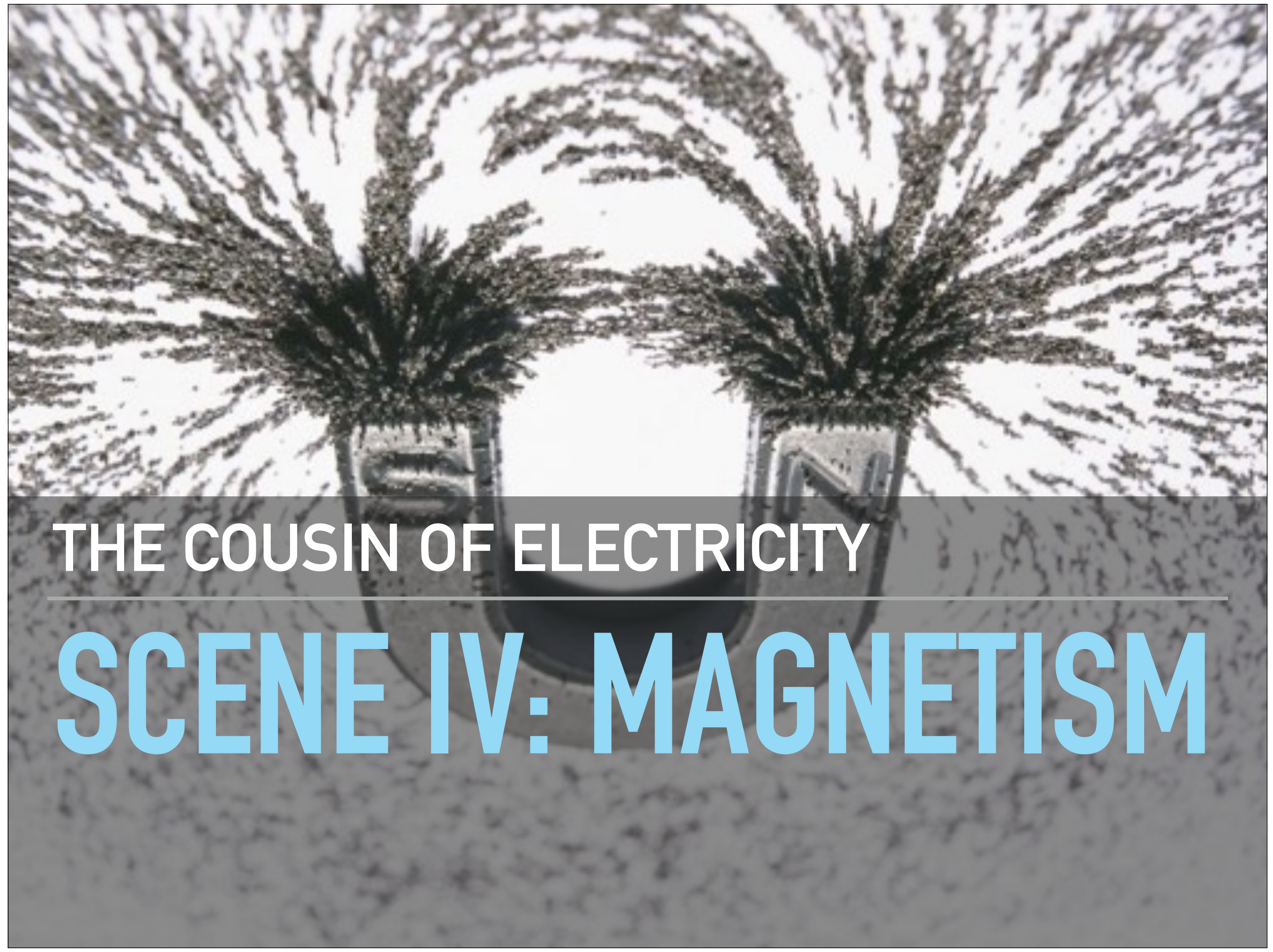
- A number of metals and some synthetic materials have also since been demonstrated to show this property of *superconductivity*



- English physicist and Nobel laureate in physics
- Discovered the electron in 1897

TAKE AWAYS FROM THE DISCOVERY OF THE ELECTRON

1. Electricity is made of subatomic particles (later dubbed *electrons*) which which are pulled from the atoms of the material
2. The electrons are all exactly the same no matter what material or substance they come from (same mass, same charge, etc.)
3. The electron is negatively charged


THE COUSIN OF ELECTRICITY
SCENE IV: MAGNETISM

- According to tradition, the first person to make a systematic study of magnetic effects was the Greek philosopher/mathematician/astronomer Thales
- Certain naturally occurring types of iron ore (called “lodestones”) were found to attract iron and, as far as the ancients could tell, nothing else
- Because the lodestones Thales studied purportedly came from his neighboring town of Magnesia, such iron-attracting materials were later dubbed *magnets*
- Thales was also the one to discover the static-electrical “amber effect,” but because magnetism was so much easier to study than electricity, of the two magnetism got most of the attention for the next two thousand years

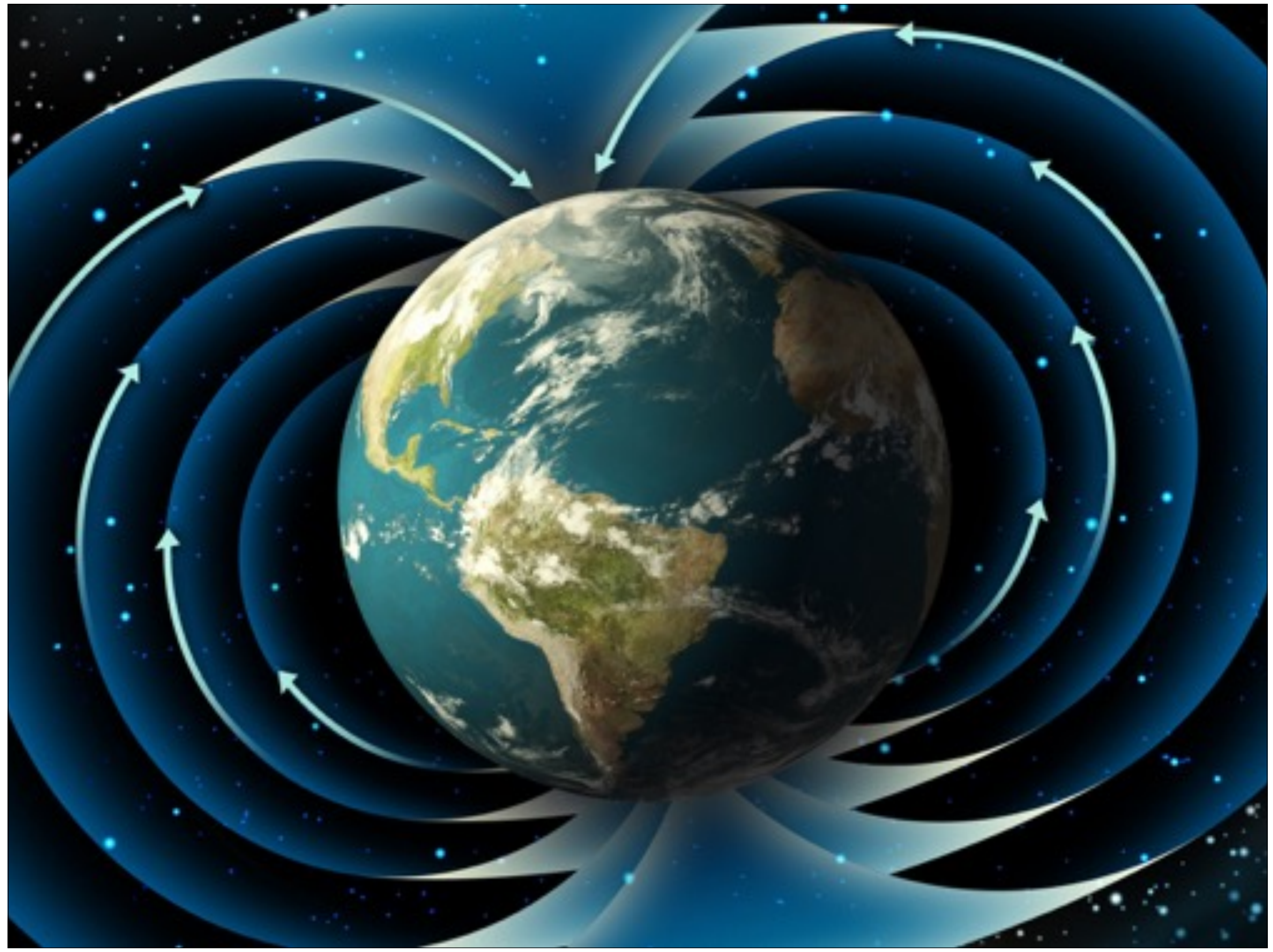
- Things we learned:
  - Magnetism could be transferred. E.g. a sliver of steel when stroked with magnetic iron would become a magnet in its own right
  - A magnetized needle, when allowed to pivot freely, would always align itself north-south. Furthermore, the same end of the needle always pointed north while the other end always pointed south

- By the 11th Century the Chinese were already taking advantage of this effect to aid in navigation

- Every magnet has two points where the magnetic effects are the strongest. These are called the *poles* of the magnet

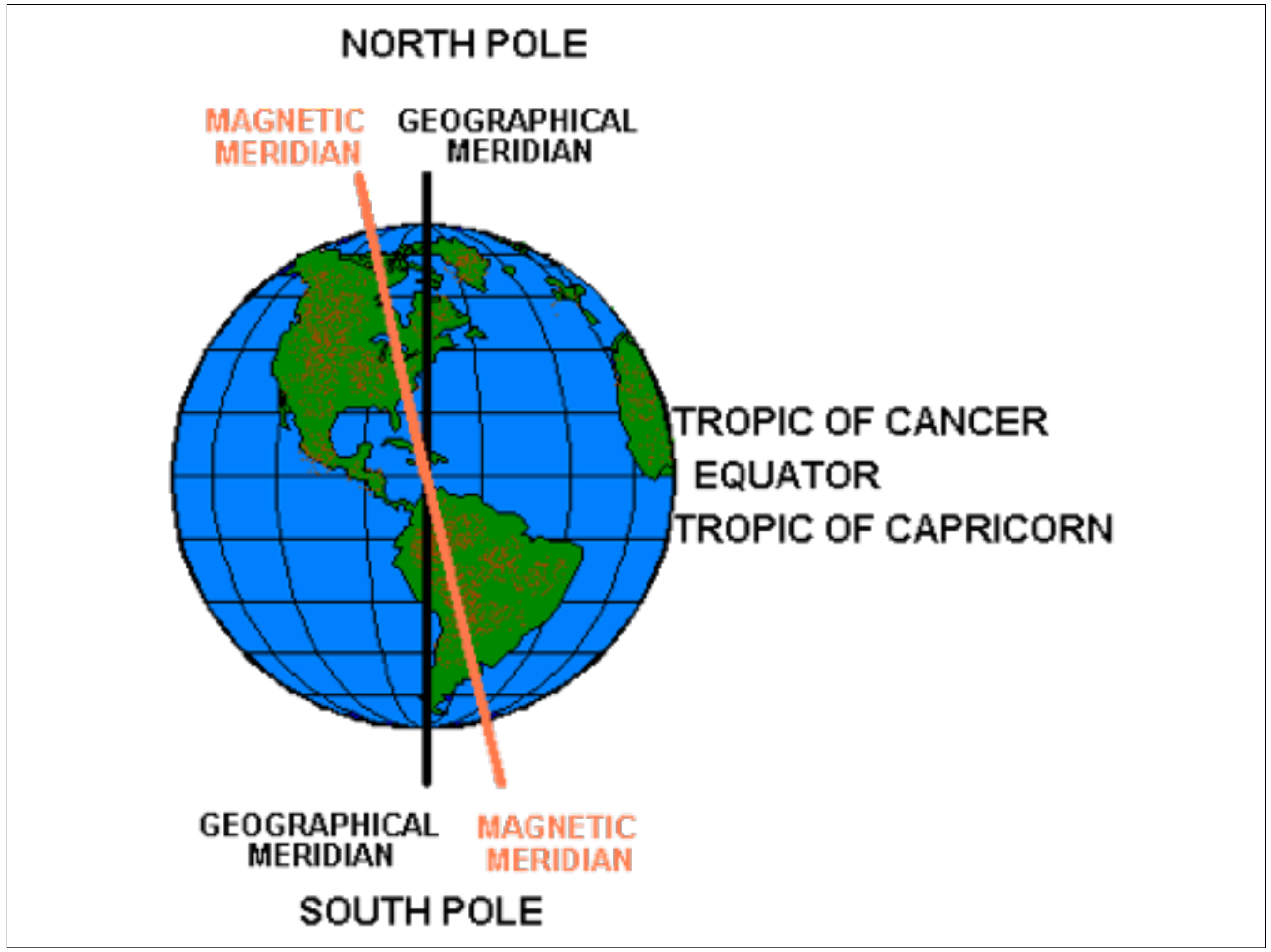
Pole – (in magnetism) a point of strongest magnetic effect

- The poles are easy to locate. For example, dip the magnet in iron filings, and the filings will invariably cluster around the poles
- As early as 1269, it became clear that there are two and only two types of poles: north and south
- No single pole is ever found by itself. Whenever a north pole can be located, a south pole can be located, too, and vice versa
- Like poles repel while unlike poles attract

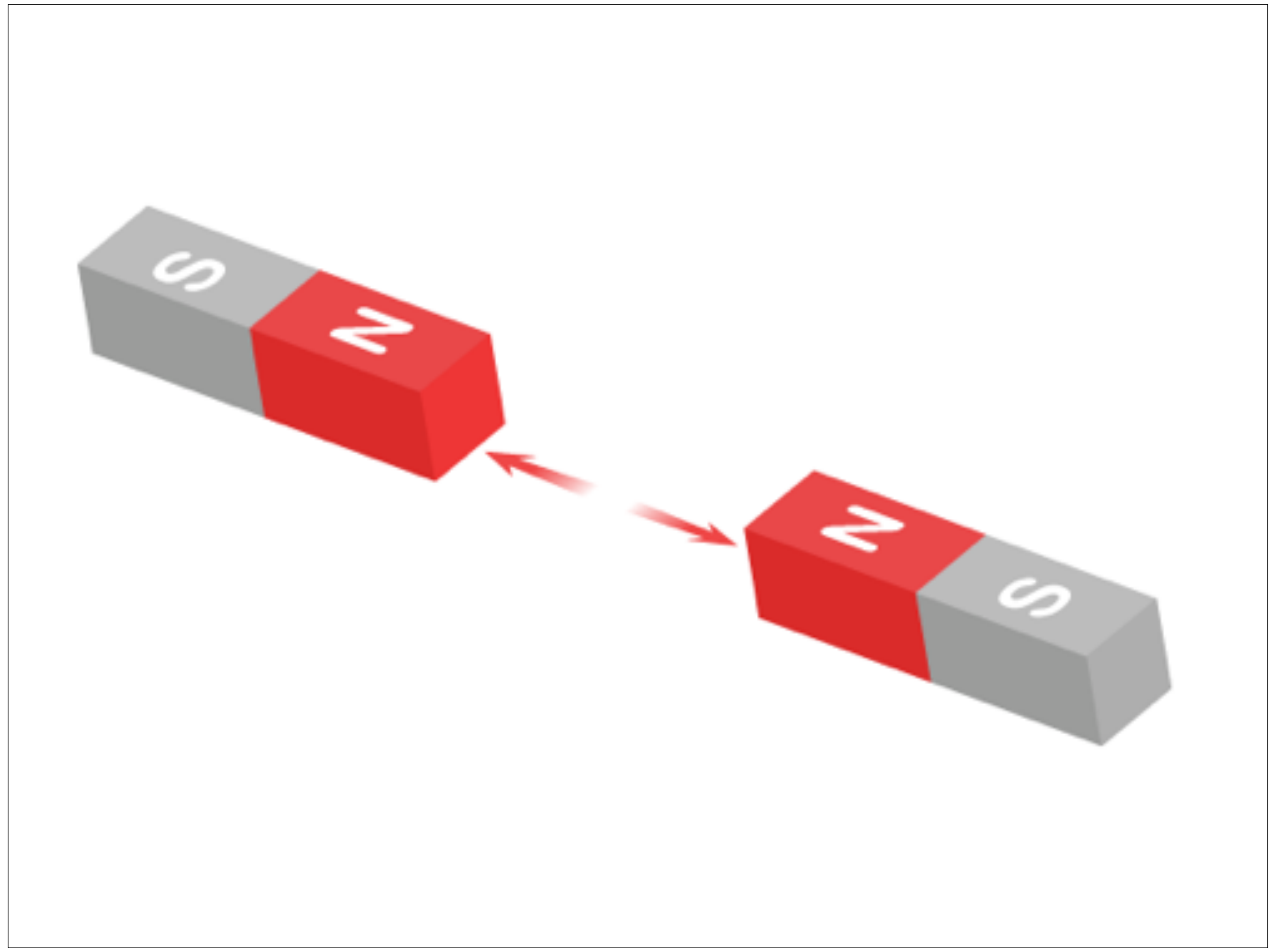


- The fact that compass needles always point north-south fascinated early physicists
- Some speculated that a huge iron mountain existed in the far north and that the magnetized needle was attracted to it
- In 1600, English physicist William Gilbert offered a more tenable solution

- Ordinary compass needles are constrained to remain perfectly horizontal. But what if it could also point upward or downward?
- Gilbert found that a needle so pivoted (in the northern hemisphere) does dip several degrees below the horizon
- He shaped a lodestone into a sphere and located its poles
    - Above the sphere's north pole, the compass needle pointed straight down, and the needle was mover closer and closer to the sphere's "equator," the needle would gradually dip less and less until it was horizontal at the equator. Moving further "south," the needle ran the same process in reverse but with its other pole gradually dipping further and further downward
    - Gilbert felt that the behavior of the compass needle with respect to the Earth was the same as with respect to the spherical lodestone and thus concluded that the Earth itself its a spherical magnet with its poles in the Arctic and Antarctic



- As it turns out, magnetic north and geographic north are not the same
- In Gilbert's time, for instance, a compass needle in London pointed 11° east of north. This angle of deviation is called the *magnetic declination*
- Magnetic declination varies from place to place and even year to year. The magnetic declination in London today is actually pretty close to zero, while in Los Angeles it's about 12° east
- Variation in declination was first noted by Christopher Columbus in his voyage of discovery in 1492, however he kept it a secret from his crew in order to keep them from panicking



- The magnetic force of attraction or repulsion varies inversely with distance
- But since no pole ever occurs alone, even in this simple situation depicted, we need to consider not only north repelling north but also south attracting north and south repelling south

CA. 1736 - 1806

CHARLES-AUGUSTIN DE COULOMB

- Coulomb got around this issue by making the bar magnetic very long so that the distance pole could be more safely ignored
- In 1785, he used his torsion balance to measured the magnetic force

MAGNETIC FORCE & INVERSE SQUARE LAW

$$F_B \propto \frac{1}{r^2}$$

*the **magnetic force** is inversely proportional to the **distance squared***

- Coulomb's experiments demonstrated that the magnetic force, like the electrostatic force and like gravity, obeys the inverse square law
- Today, we use "B" to represent magnetism (since "m" is already taken by mass)

CA. 1777 - 1851

HANS CHRISTIAN OERSTED

- Until the early 1800s, electricity and magnetism were regarded as two entirely independent phenomena
- In 1820, Hans Christian Oersted was experimenting with electricity and magnetism and found that a stationary charge and a magnet won’t influence each other
- But! when he placed a compass near a wire, as soon as he connected the battery and current began to flow, the compass needle deflected!

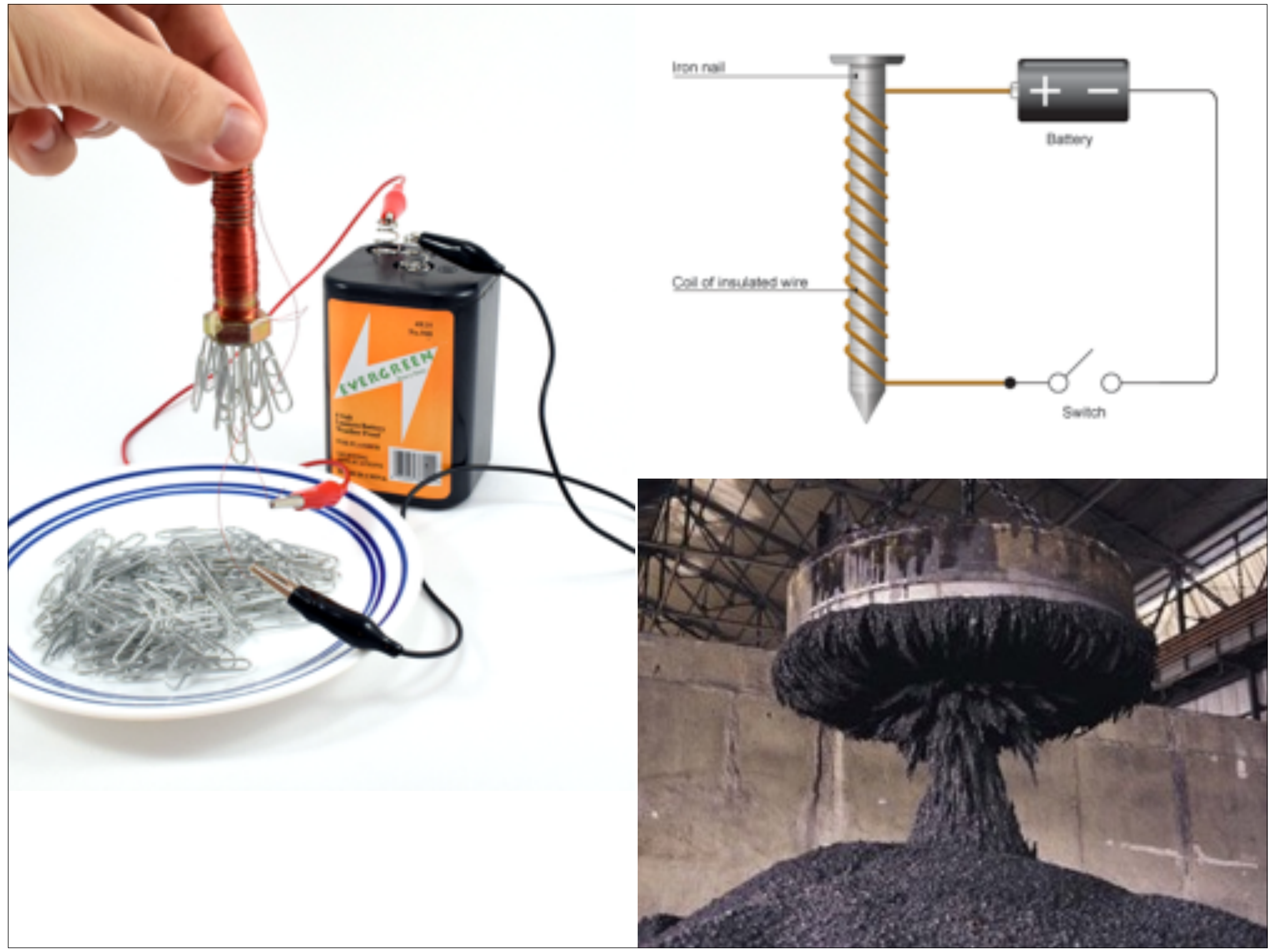
A MAGNETIC FIELD IS PRODUCED BY THE MOTION OF ELECTRIC CHARGE

- It was further demonstrated that a current carrying wire could also be used to magnetize previously unmagnetized iron
- French physicist André-Marie Ampère found that two parallel wires would attract each other when current was flowing in the same direction and would repel each other if current was flowing in opposite directions

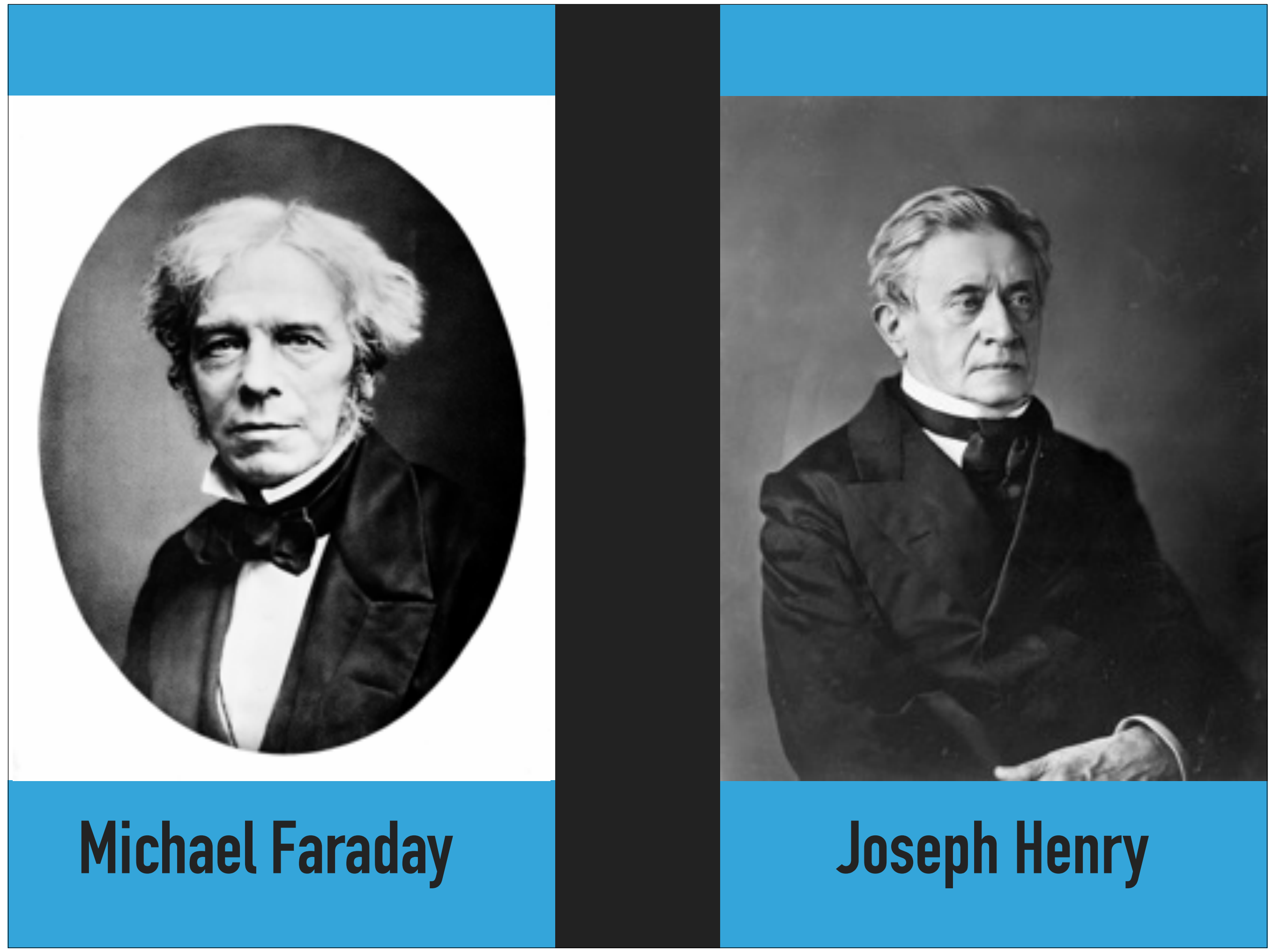
AMPÈRE'S LAW

$$B \propto \frac{I}{r}$$

*the strength of the **magnetic field** is directly proportional to the **current** inversely proportional to the **distance** from the wire*

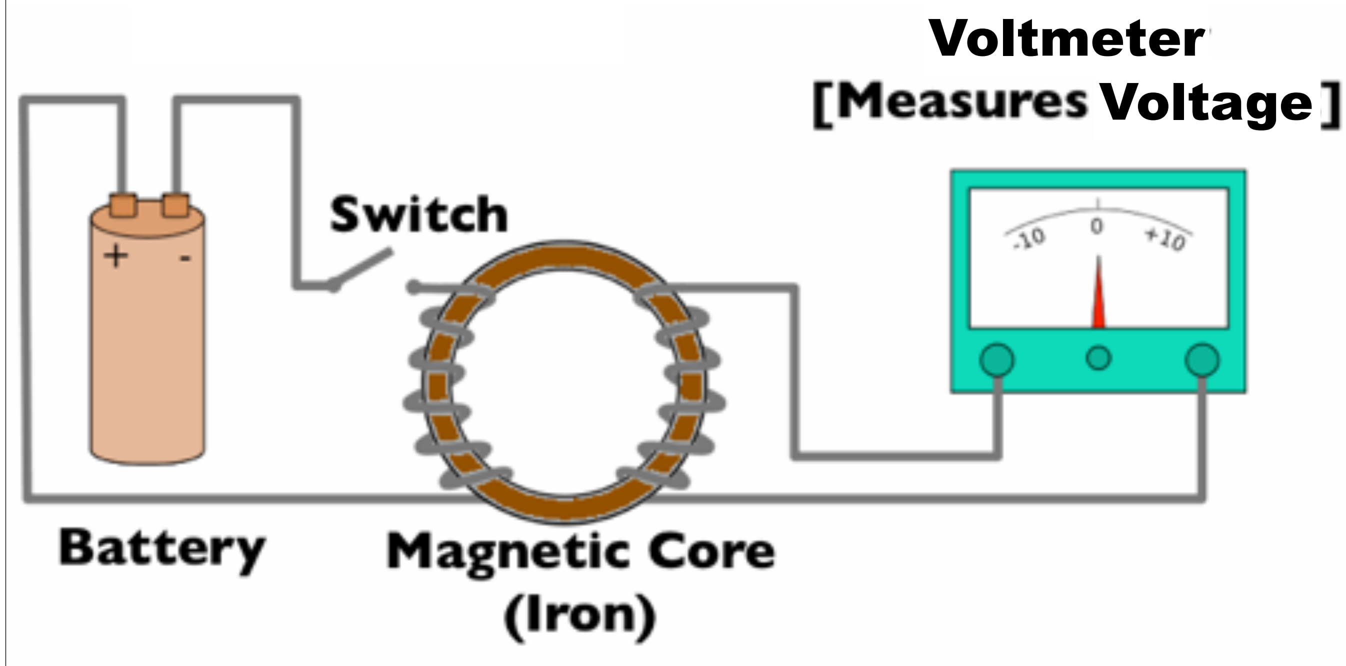


- By coiling a current-carrying wire around an iron core, one can create an *electromagnet*
- By 1831, Joseph Henry had produced an electromagnet, of no great size, that could lift a ton of iron
- For reference, a toy magnet ~300 gauss, good bar magnet ~3000 gauss, great bar magnet ~10,000 gauss, electromagnet ~60,000 gauss easy



- In 1831, two physicists, Michael Faraday in England and Joseph Henry in the United States, independently discovered that magnetism could produce an electric current in a wire

ELECTROMAGNETIC INDUCTION

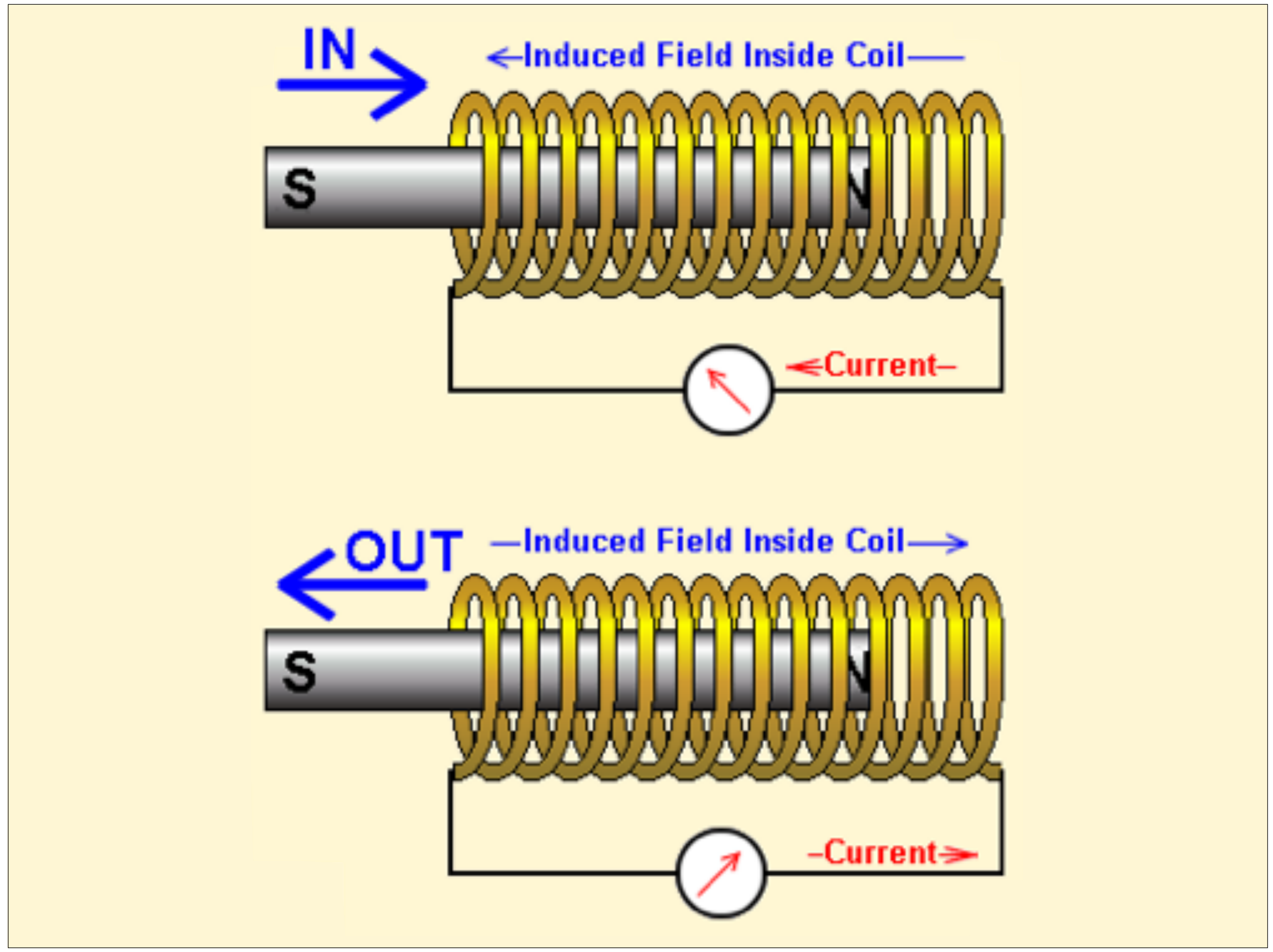


- Even with the switch closed and current running, no reading on the voltmeter
- However! while the switch was being closed (or opened) the voltmeter needle flick indicating a momentary pulse of current
- A *changing* magnetic field will produce a voltage

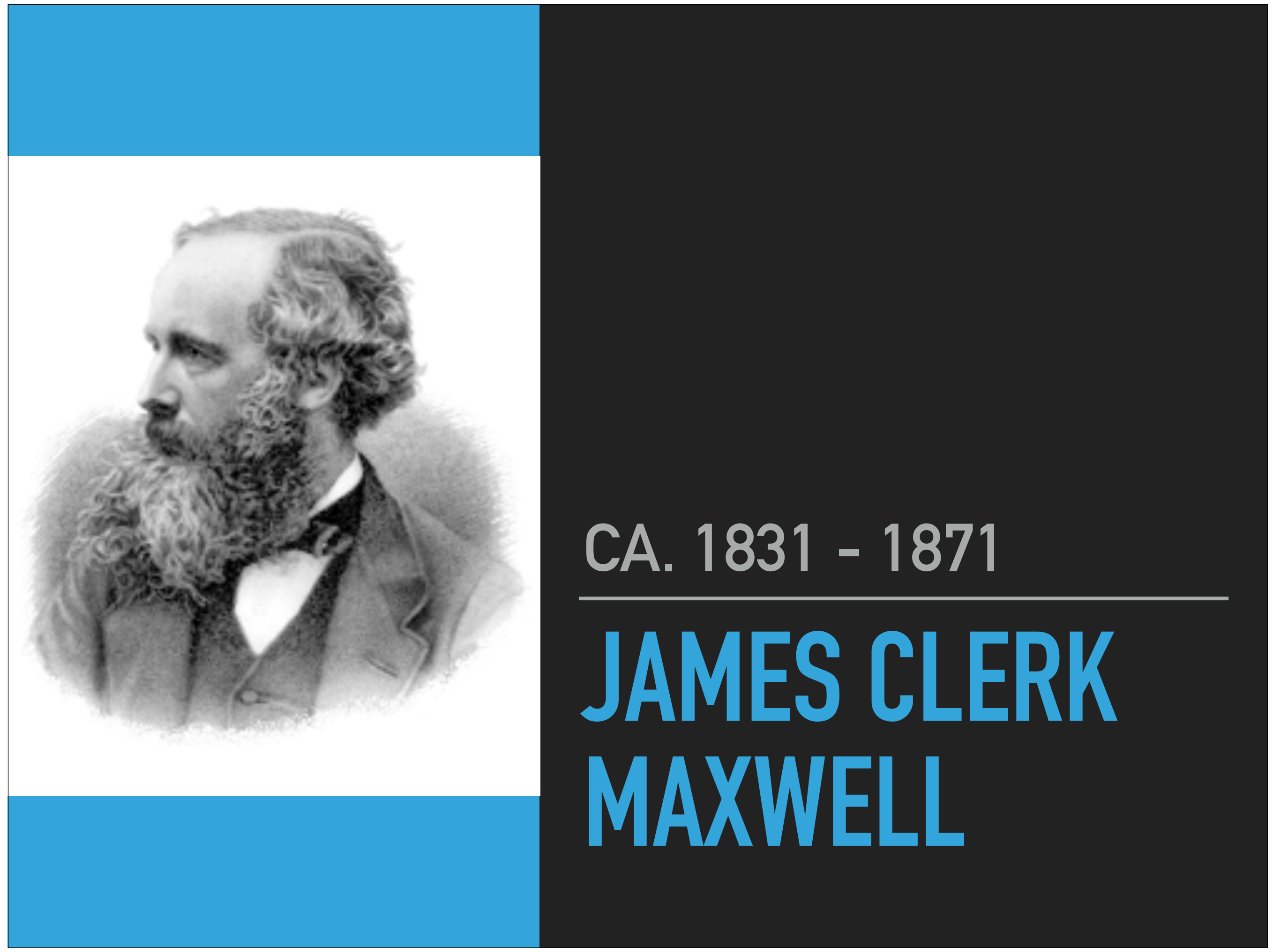
AN ELECTRIC FIELD IS PRODUCED BY A **CHANGING** MAGNETIC FIELD

AN INDUCED VOLTAGE ALWAYS GIVES RISE TO A CURRENT WHOSE MAGNETIC FIELD OPPOSES THE ORIGINAL MAGNETIC FIELD WHICH PRODUCED IT

Lenz's Law



- Try to push the magnet *into* the coil and current will counter-clockwise, creating a magnetic field that *repels* the incoming magnet
- Try to pull the magnet *out of* the coil and current will run clockwise, creating a magnetic field that *attracts* the outgoing magnet



- As influential to Electromagnetism as Newton was to Mechanics
- Maxwell reduced all current knowledge down into a linked set of equations

I. The electric field leaving a volume is proportional to the charge inside

— GAUSS'S LAW

- More charge packed closer together produces a stronger electric field

II. There are no magnetic monopoles

— GAUSS'S LAW FOR MAGNETISM

- There is never a north pole without a south pole, or vise versa

III. The voltage induced in a closed loop is proportional to the rate of change of the magnetic field the loop is exposed to

— FARADAY'S LAW

- The more dramatically the magnetic field changes, the bigger the induced voltage

IV. The magnetic field induced around a closed loop is proportional to the electric current plus the rate of change of the electric field

— AMPÈRE'S LAW

- The more current flows and/or the more dramatically the electric field changes, the bigger the induced magnetic field

THE MAXWELL EQUATIONS

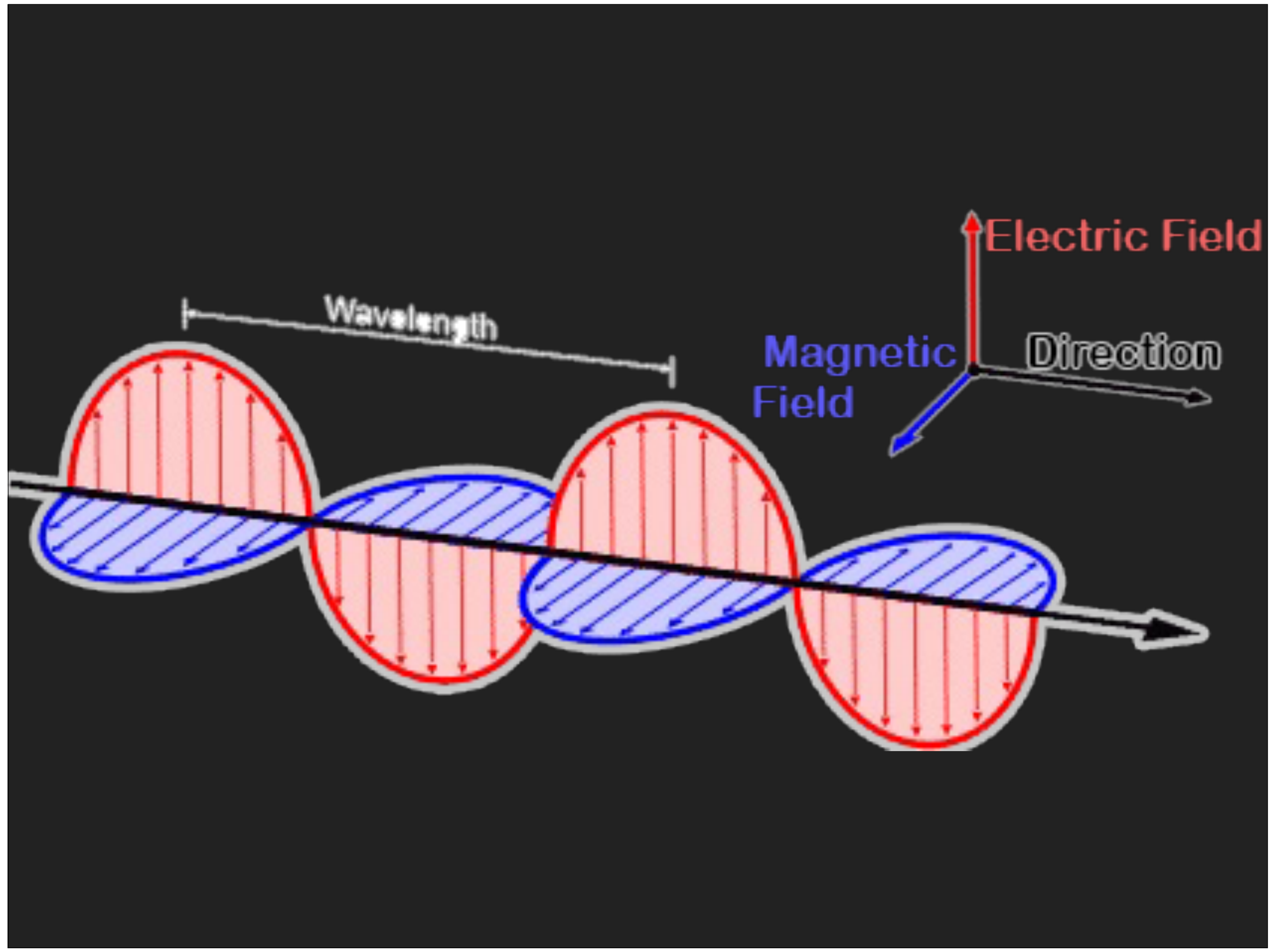
I. $\nabla \bullet \mathbf{E} = \rho / \varepsilon_0$

II. $\nabla \bullet \mathbf{B} = 0$

III. $\nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t}$

IV. $\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \dfrac{\partial \mathbf{E}}{\partial t} \right)$

- One important takeaway is that in order for these equations to be valid, it seems impossible to consider an electric field or a magnetic field in isolation



- Because changing electric fields cause magnetic fields and changing magnetic fields cause electric fields, Maxwell predicted the existence of electromagnetic waves
- Maxwell could even calculate the velocity of such a wave by taking the ratio of corresponding forces between electric changes and between magnetic poles. That velocity, it turns out, was the speed of light

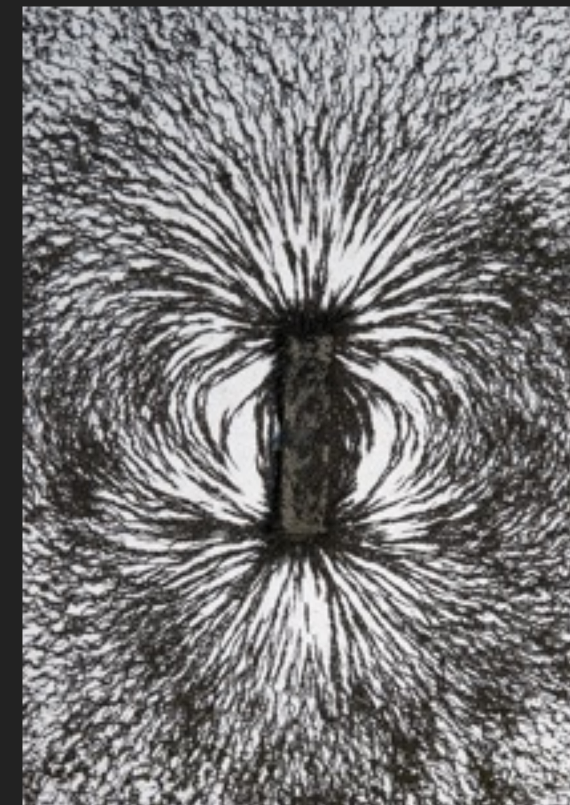
"The agreement of the results seems to show that light and magnetism are affections of the same substance, and that light is an electromagnetic disturbance propagated through the field according to electromagnetic laws."

James Clerk Maxwell

- Maxwell concluded that this was no mere coincidence, but that light must itself be electromagnetic radiation

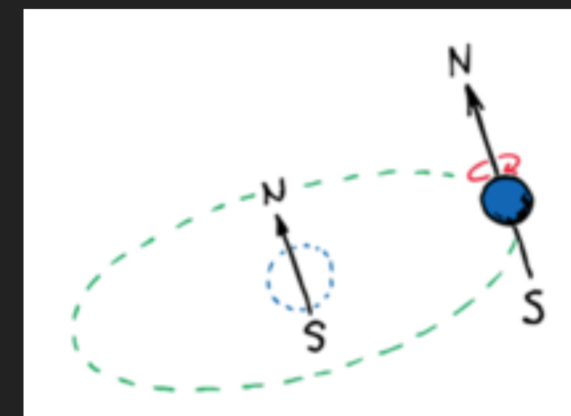
SANITY CHECK

- So where's the motion of electric charge in a bar magnet?



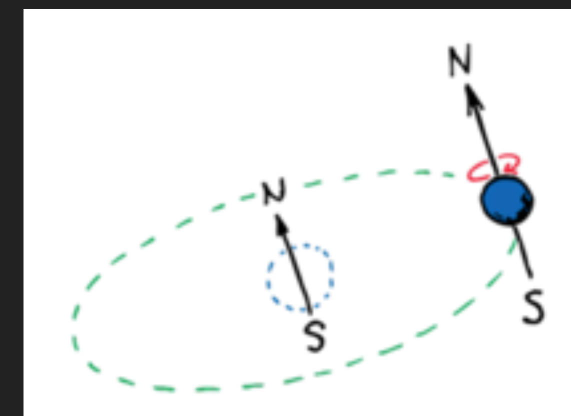
SANITY CHECK

- *While the magnet as a whole may be stationary, it is made of atoms whose electrons are in constant motion around the atomic nuclei*
- *This moving charge constitutes a tiny current and produces a magnetic field*



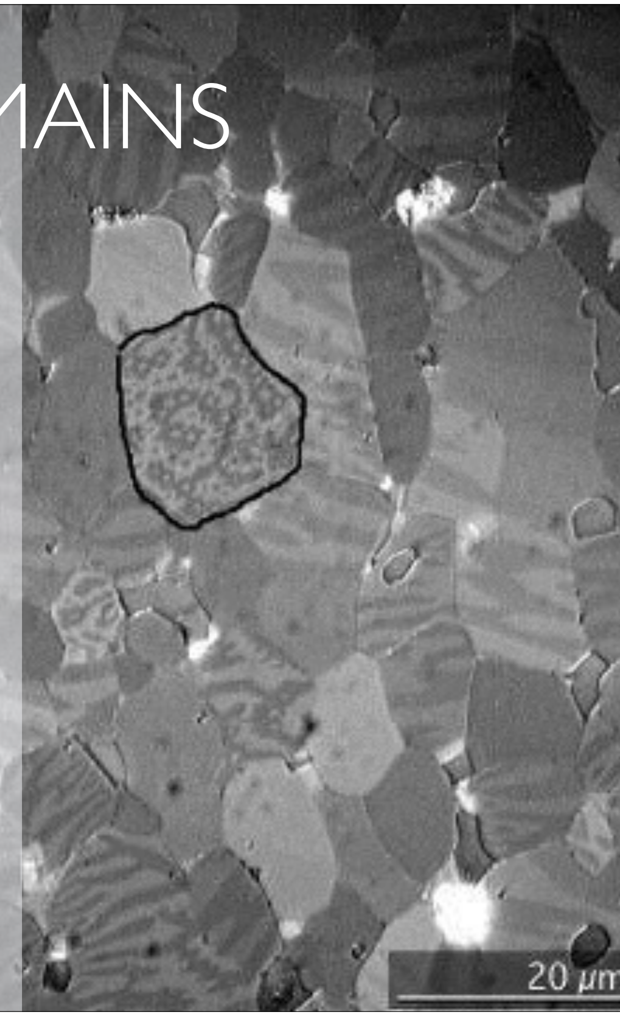
SANITY CHECK

- *More important, electrons can be thought of as spinning about their own axes like tops*
  - *The spinning electron creates another magnetic field*
- *Typically, the field due to the electron spin predominates over the field due to orbital motion*



DOMAINS

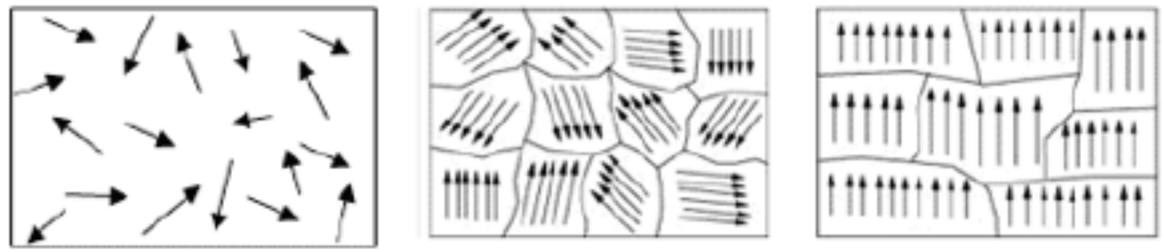
- The magnetic fields of individual iron atoms are strong
  - Interactions among adjacent iron atoms cause large clusters of them to line up with one another
  - These clusters of aligned atoms are called ***magnetic domains***



DOMAINS

- The difference between an ordinary piece of iron and an iron magnet is the alignment of the domains
  - In common iron nail = randomly oriented
  - But in presence of a strong magnetic field, the aligned domains grow
- If a permanent magnet is dropped or heated, the domains may jostle out of alignment

DOMAINS



Non-Magnetic Material
(no domains)

Magnetic Material
(domains, but not lined up)

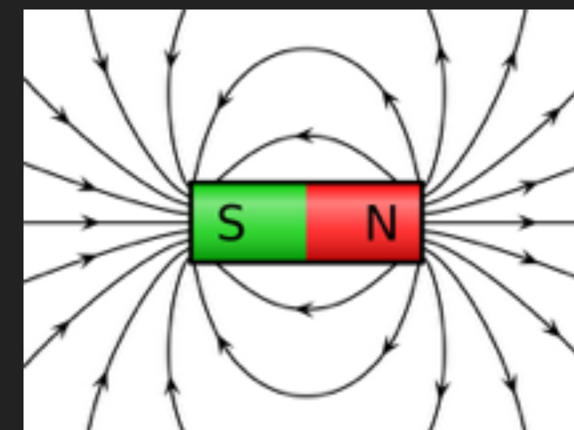
Magnet
(domains, and all are lined up)

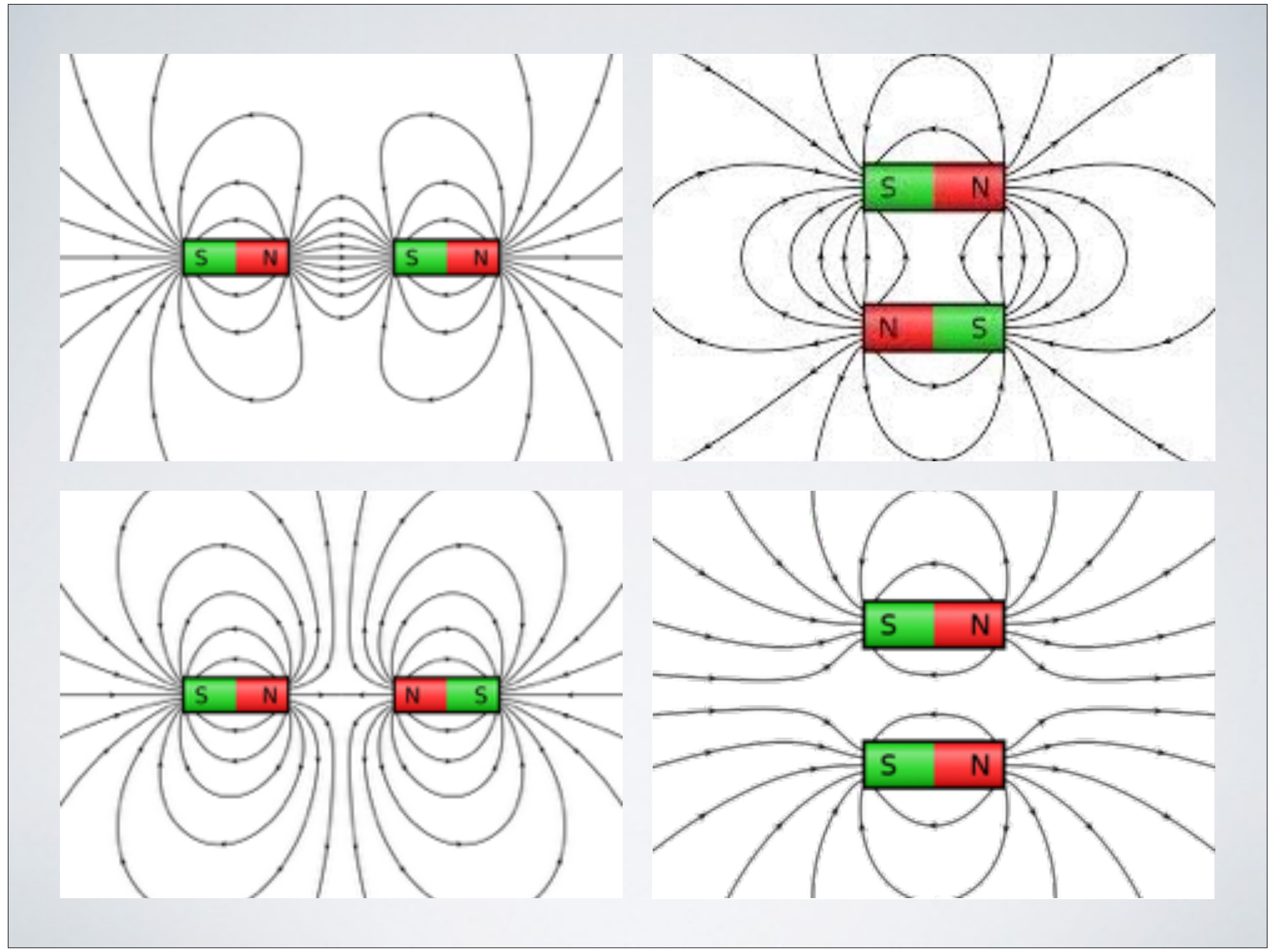
MORAL OF THE STORY

- *Magnetic fields are produced by the motion of electric charge*

MAGNETIC FIELDS

- Facts:
  1. field lines point from north to south
     - (the direction a compass needle would point)
  2. field lines never cross
  3. density of field lines is proportional to the strength of the field





S
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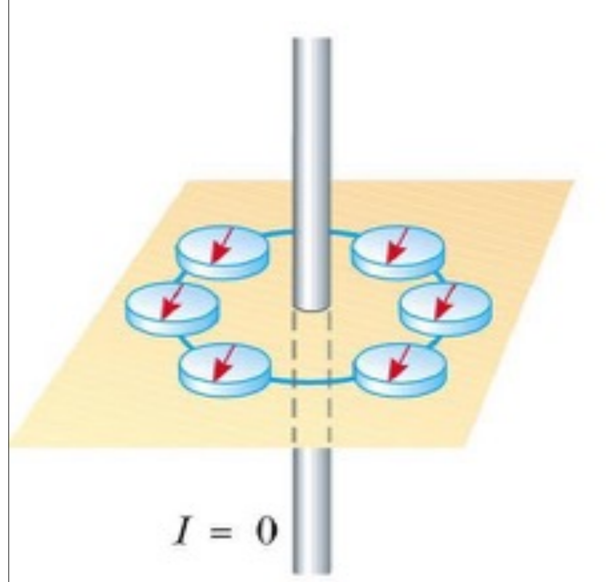
MAGNETISM & ELECTRIC CURRENTS

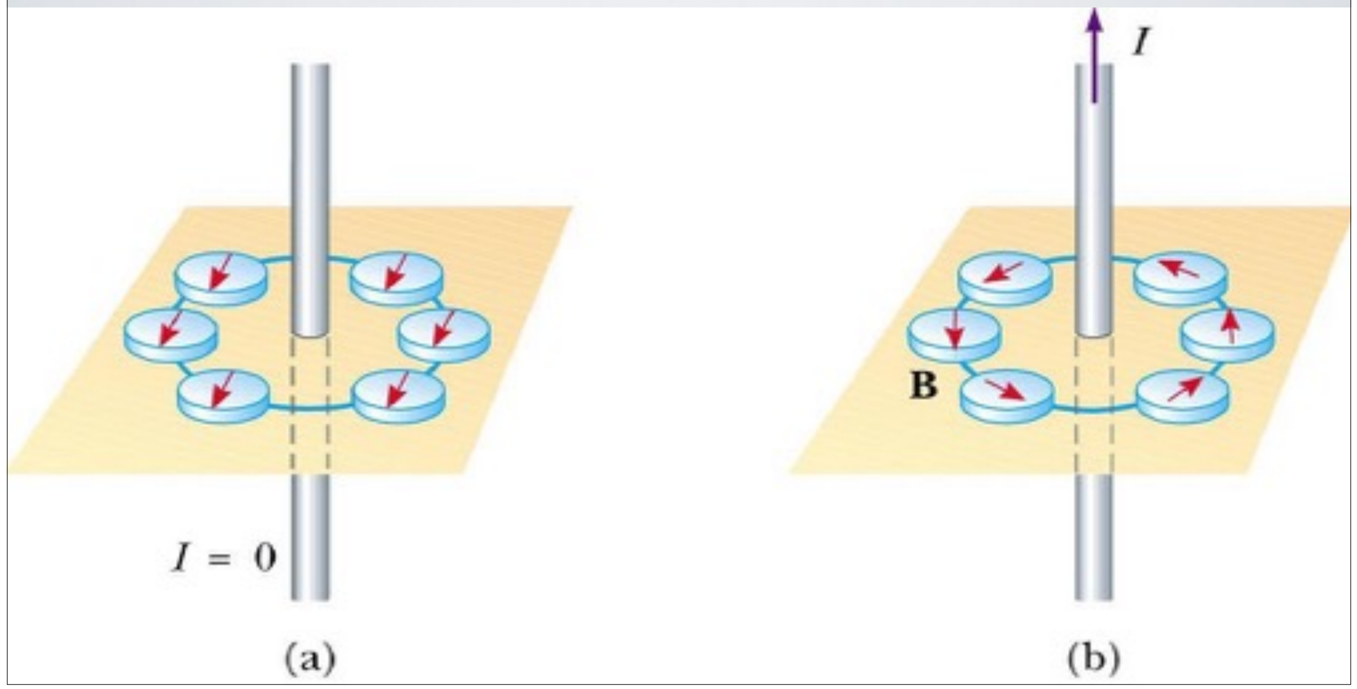
(a) When there is no current in the wire, the compasses align with Earth's magnetic field



(a)

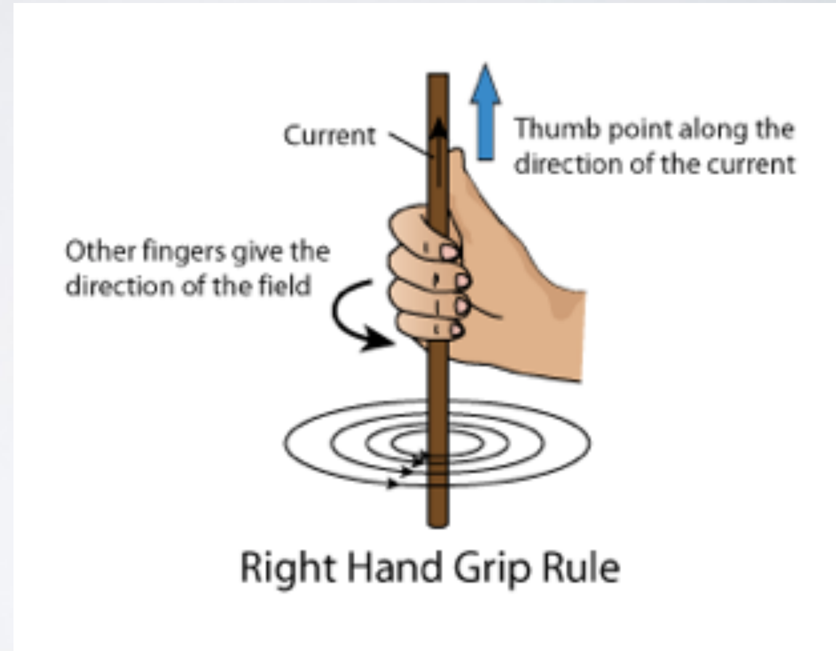
MAGNETISM & ELECTRIC CURRENTS

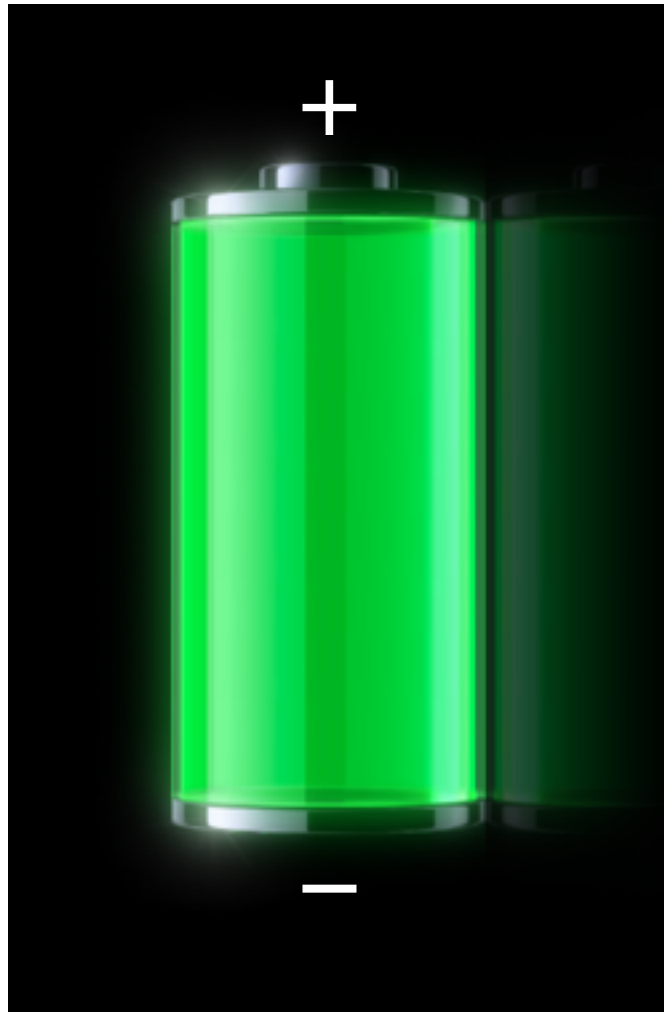
(b) When there is a current in the wire, the compasses align with the stronger magnetic field near the wire



RIGHT HAND RULE, PART 1

- The ***right hand rule*** is a tool to help us figure out the *direction* of the magnetic field relative to the current



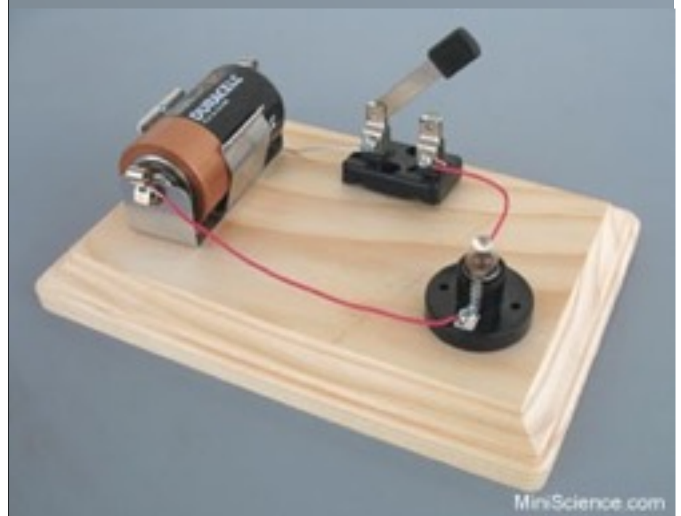


BATTERIES & VOLTAGE

- 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
- $\boxed{I = \Delta Q/\Delta t}$
  - 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.

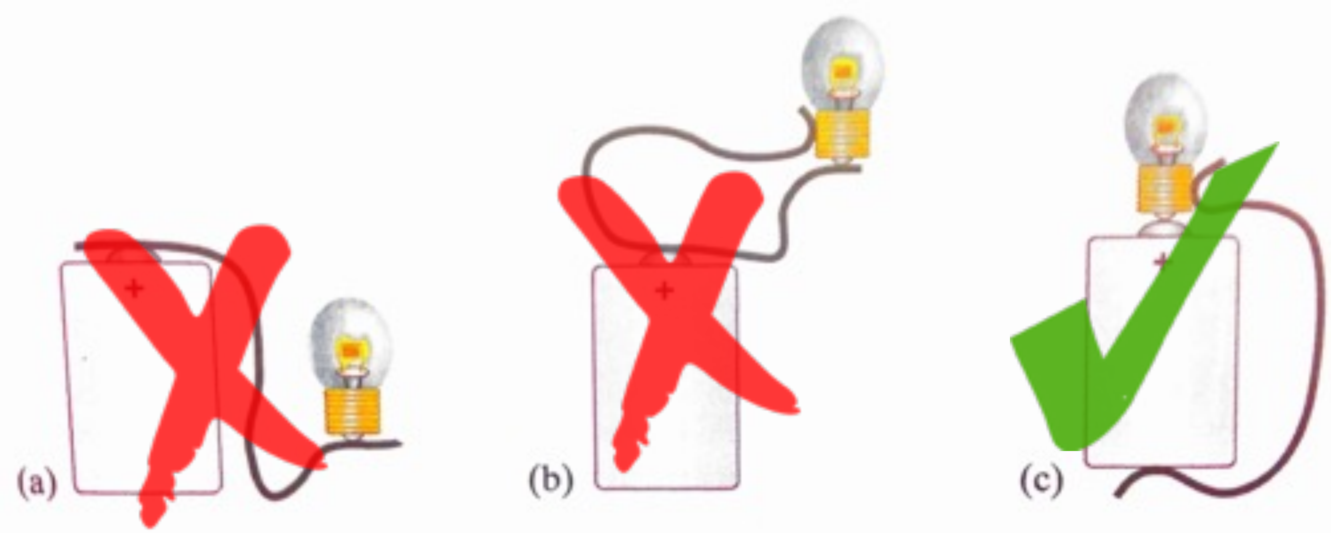
a) How much charge passed through any point in the circuit?

b) How many electrons would this be?

a) Ans. ΔQ = 600 C
b) Ans. 3.8×10^{21} electrons

SANITY CHECK

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



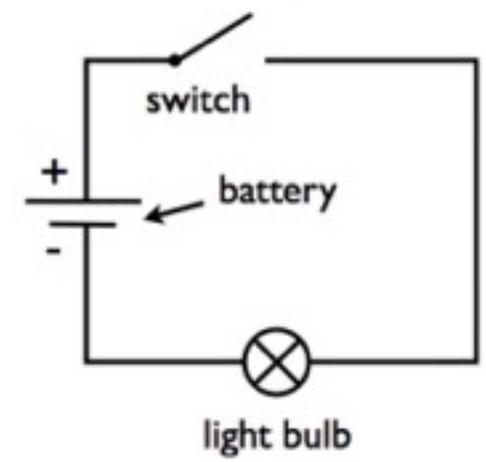
No loop for current to flow around

Loop, but no potential difference to push charge

All good!

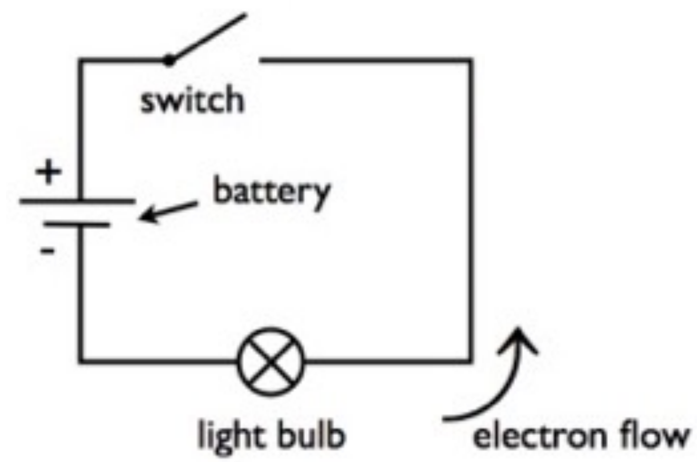
ELECTRIC CURRENT

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



ELECTRIC CURRENT

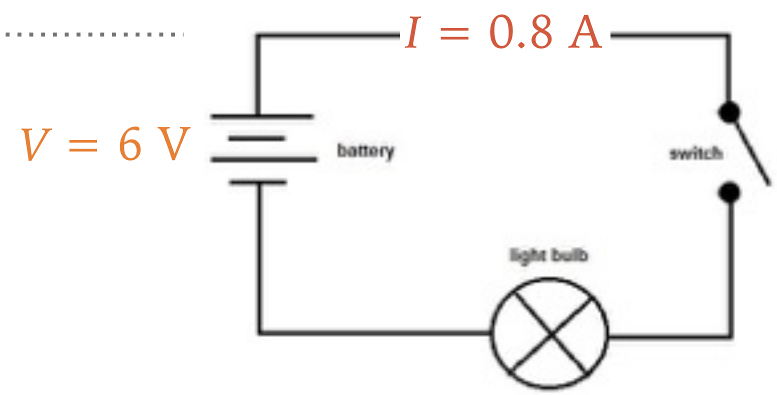
- When the conventions of positive and negative charge were invented over 200 years ago, it was thought that positive charge flowed in the wire
- Current, sometimes referred to as ***conventional current***, is therefore said to run from *positive to negative*
- The idea stuck (sorry)

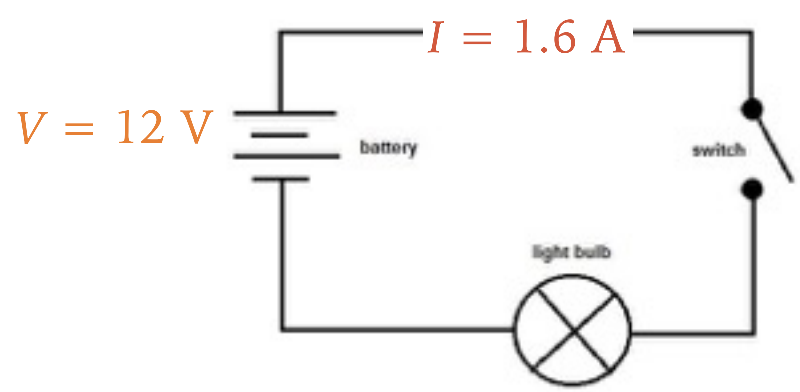


OHM'S LAW

- 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

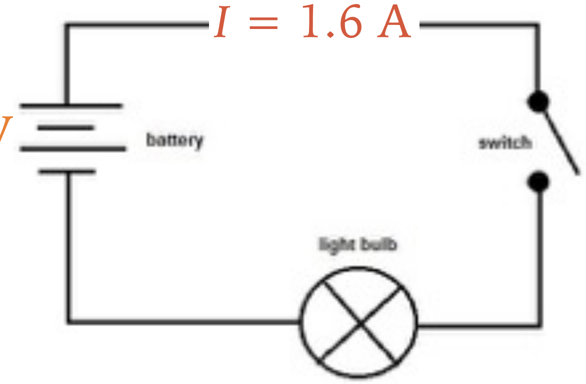

$I = 0.8$ A
$V = 6$ V
battery
switch
light bulb

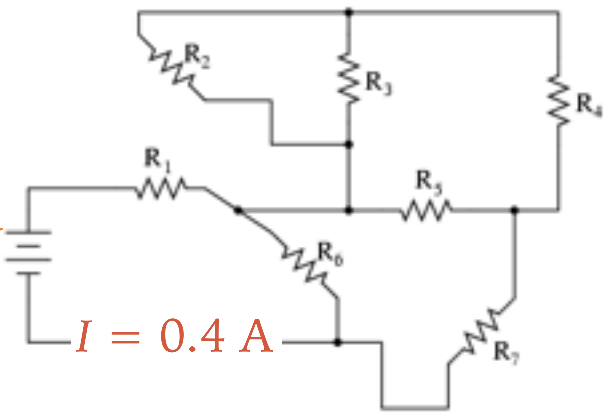

$I = 1.6$ A
$V = 12$ V
battery
switch
light bulb

OHM'S LAW

$I = 1.6\ \text{A}$

$V = 6\ \text{V}$ / $V = 12\ \text{V}$

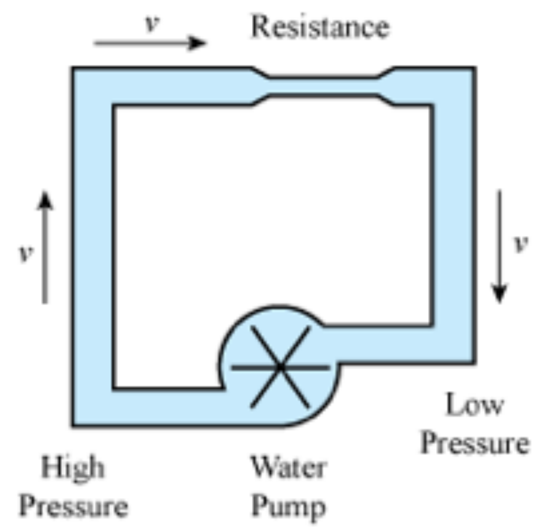




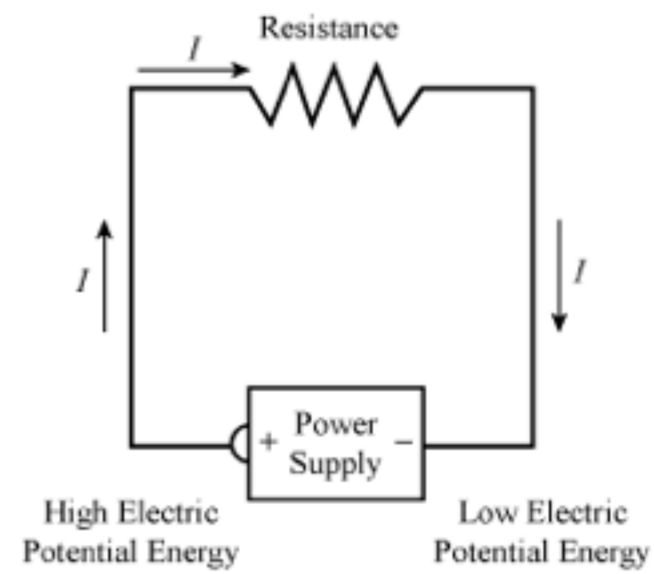
$V = 6\ \text{V}$ / $V = 12\ \text{V}$

$I = 0.4\ \text{A}$

OHM'S LAW

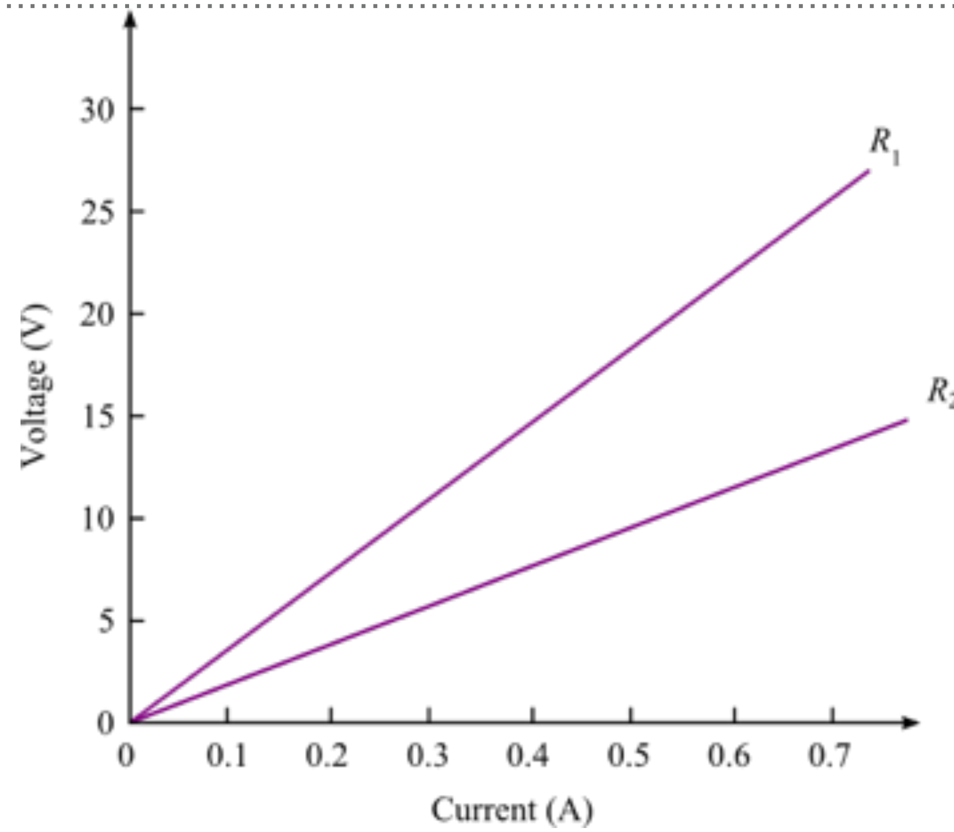


v
Resistance
v
v
High
Pressure
Water
Pump
Low
Pressure



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**)
- $\boxed{V = IR}$

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?

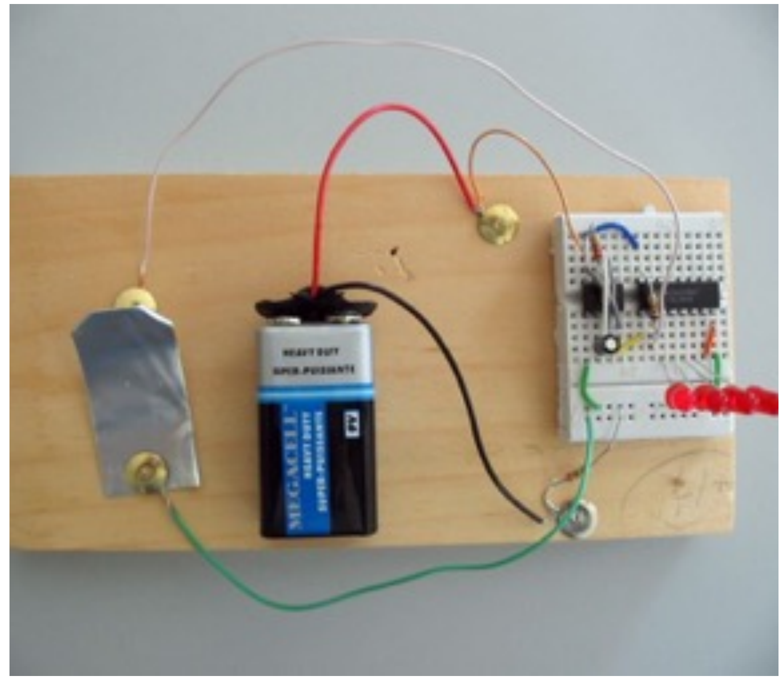
b) How much charge passes through in 15 min?

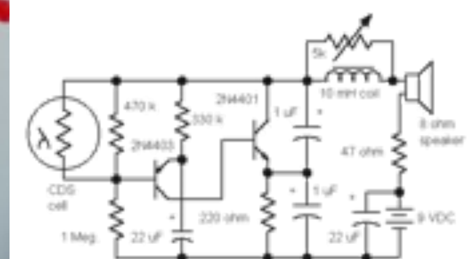
a) Ans. $R = 13.3\ \Omega$

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





Building Circuits

CIRCUIT DIAGRAMS

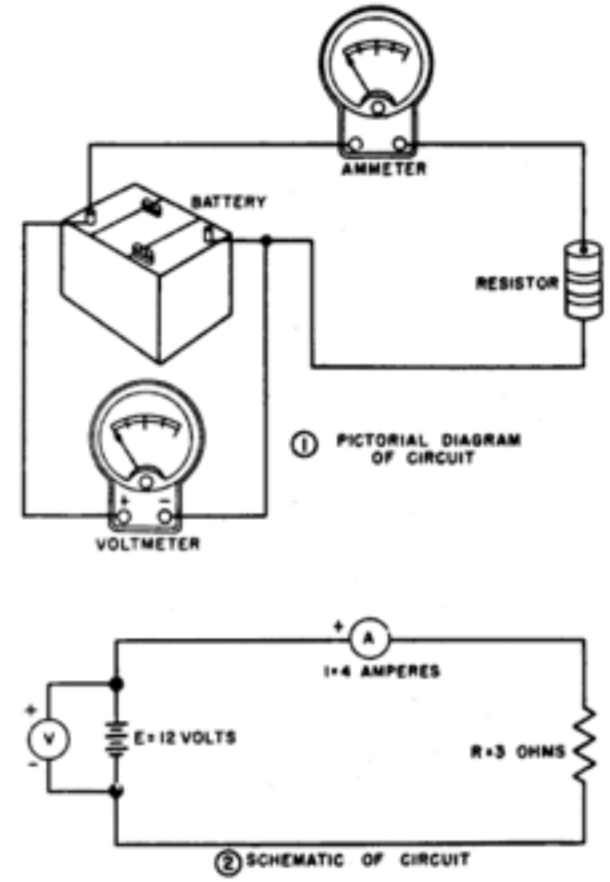
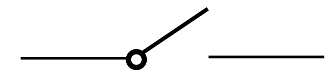
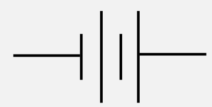
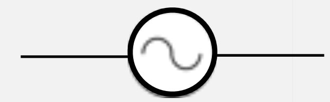
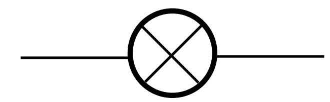
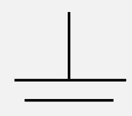
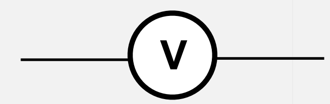
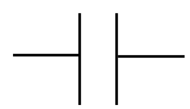
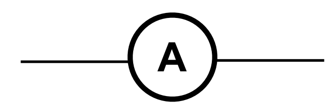
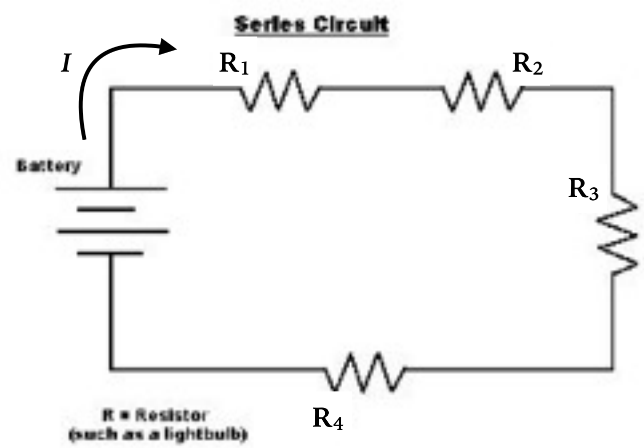


Figure 48. Diagram of a basic circuit.

CIRCUIT DIAGRAMS

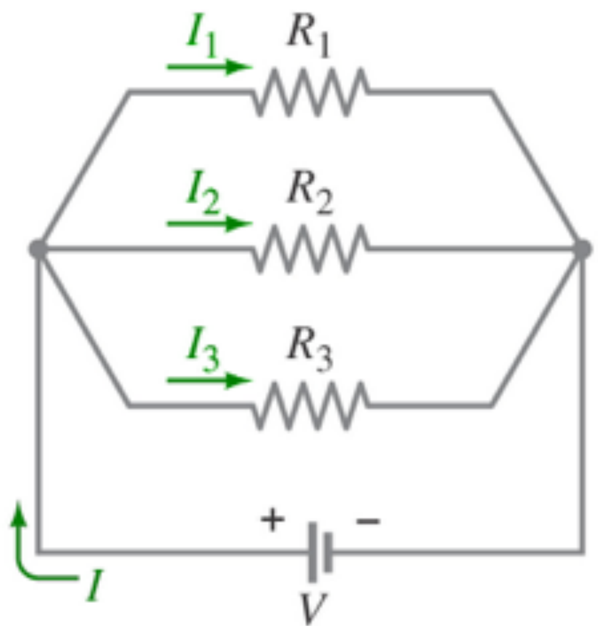
	Wire		Switch
	DC Battery		AC Voltage Source
	Resistor		Lamp
	Ground		Voltmeter
	Capacitor		Ammeter

SERIES & PARALLEL



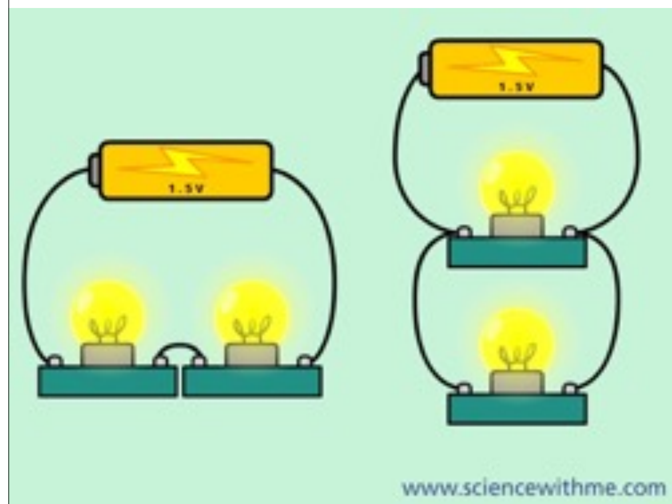
- When two or more resistors are connected end to end, they are said to be connected in ***series***
- Any charge that passes through R_1 will also pass through R_2 and then R_3, etc.
  - Hence, the same current I will pass through each resistor

SERIES & PARALLEL



- 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***
- $I = I_1 + I_2 + I_3$

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