Enlightened:
What we've learned from planets and light

An Ancient Quest

- Since earliest human history, science has advanced primarily through our quest to understand two things:
  - The motion of the sun, stars, planets, and other heavenly bodies.
  - The nature of light.
- The first is arguably how “science” began (leading to the creation of what we now call “physics”), while the second has led us to profound and surprising discoveries about the nature of reality itself.
  - Big things happen when the two are combined

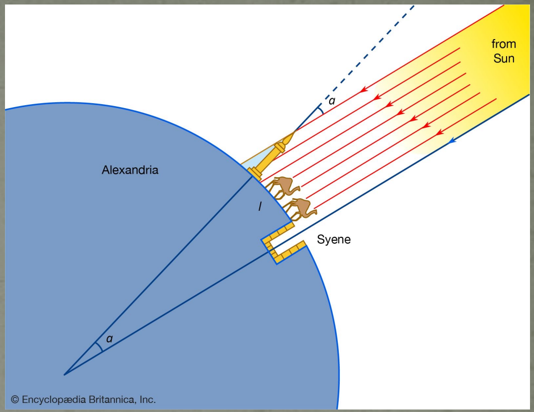
A Brief History of Gravity…

- Contrary to some claims, most ancient cultures understood that the Earth was spherical:
  - The Greeks knew this by 500 BC at the latest
  - In his treatise "One the Heavens" (~350 BC), Aristotle put forth a longwinded (and totally nonsense) philosophical argument that all things must fall toward the center of the Earth
    - You could argue that this was kinda sorta gravity, but it also meant Earth had to be the center of the solar system (put a pin in that!)
  - Interestingly, about a century later, Aristarchus of Samos proposed a *heliocentric* system, but it never caught on and was largely forgotten.*

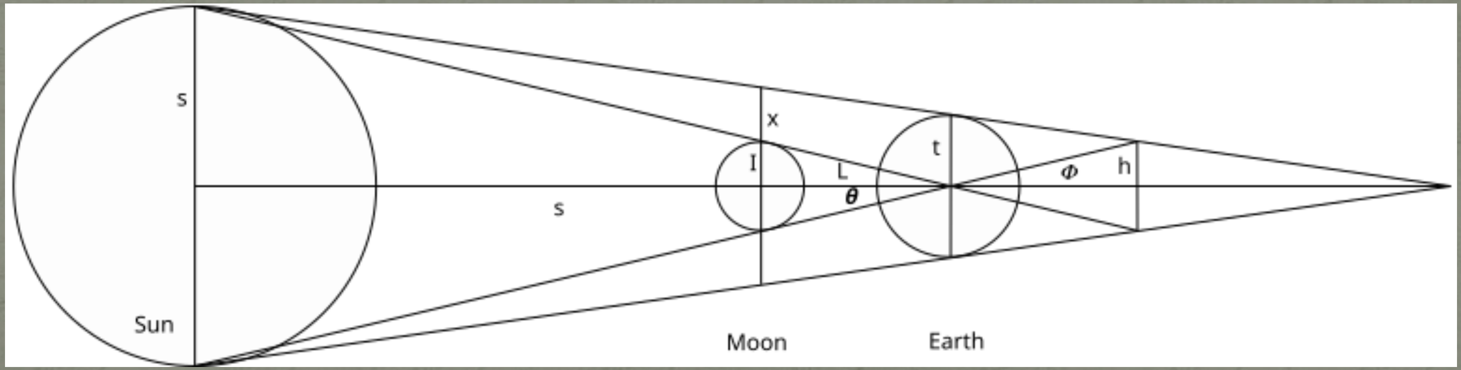
*See "The Sand Reckoner" by Archimedes

The Size of the Earth and Moon

- In 240 BC, Eratosthenes estimated the size of the Earth by comparing shadows in two different locations
  - Correct to about 10%

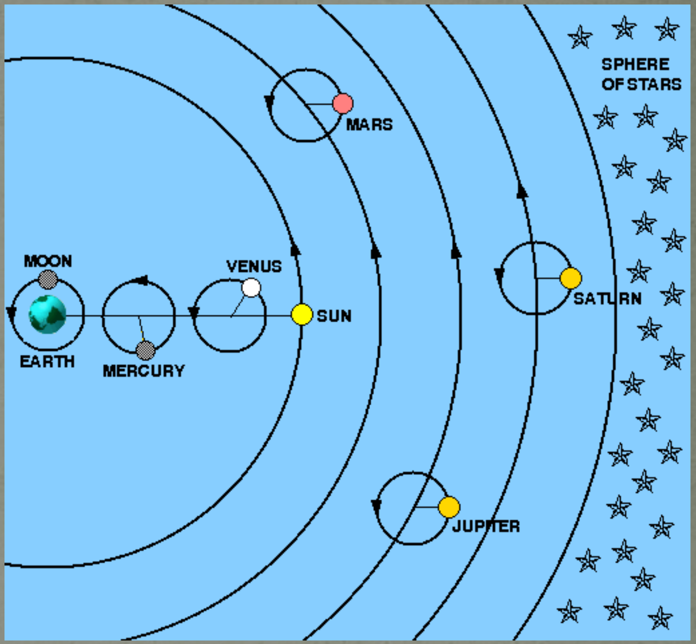


- Around 150 BC, Hipparchus used the fact that a total solar eclipse in Hellespont was only 4/5 of an eclipse in Alexandria to estimate the distance to the Moon
  - Correct to about 20%



Ptolemy's Solar System

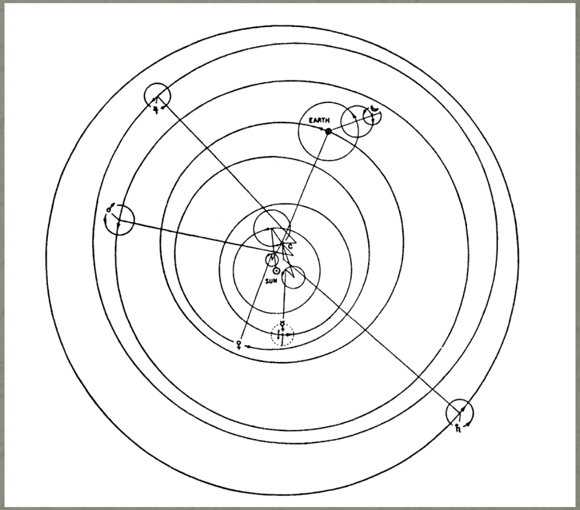
- Like most of the ancients, Ptolemy believe the sun, Moon, and planets all orbited the Earth
- The problem was "retrograde" motion, in which planets appeared to reverse course.
- In his masterwork, "Almagest" (150 AD), Ptolemy solved this problem by adding "epicycles" (circles on circles)



- This model was *very* accurate.
  - Correctly predicted observed planetary motion as well as solar and lunar eclipses.
  - Became the accepted model for the next 1500 years!

Return of Heliocentrism

- In 1543, Nicolaus Copernicus* published "On the Revolutions of the Celestial Spheres", in which he proposed that the Earth and the other planets orbit the sun.
- This was famously championed by Galileo in "Dialogue Concerning the Two Chief World Systems" in 1632**, but there was a problem
  - Precise observational data (particularly by Tycho Brahe) were not consistent with circular orbits.
  - In order to fit the data, Copernicus added – you guessed it – epicycles!
  - Although closer to what we now accept as reality, the model was really no better than Ptolemy's

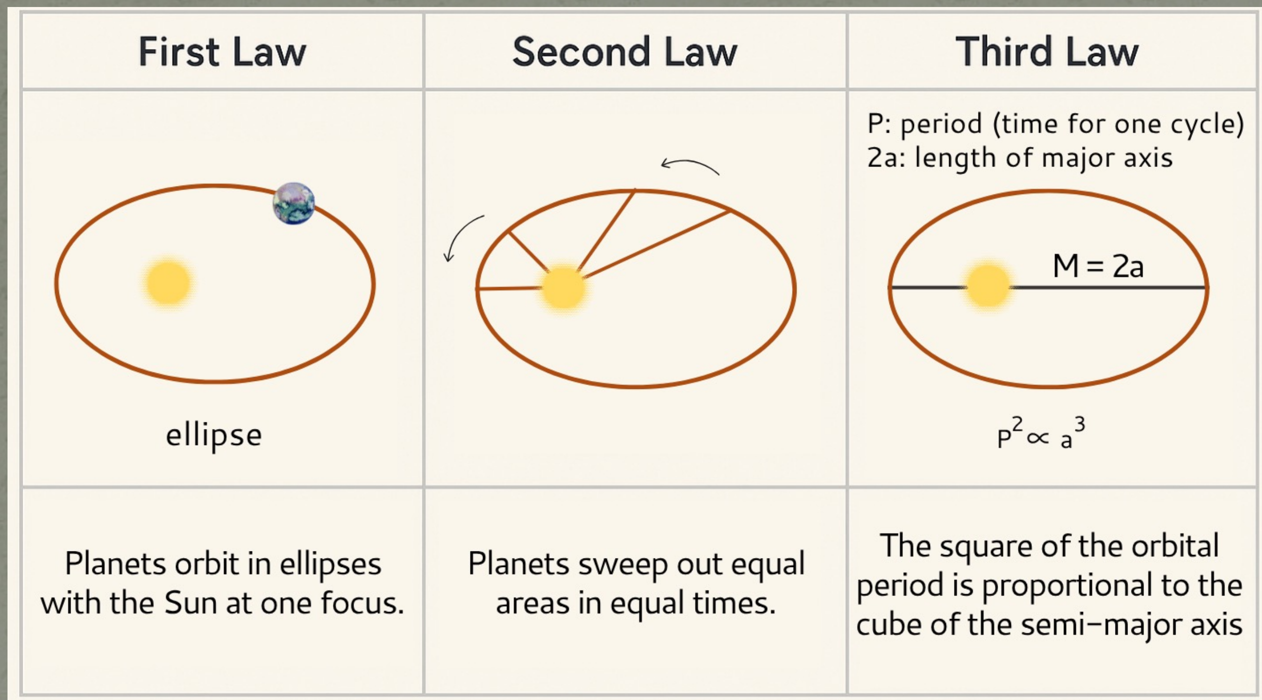


*unaware of Aristarchus!

** See "Galileo's Daughter", by Dava Sobel and "Galileo, Science, and the Church", by Jerome Langford

Enter Kepler

- Between 1609 and 1619, Johannes Kepler showed that you could explain ALL the observational data exactly with three simple laws:



- These were no more motivated than Ptolemy's or Copernicus' epicycles, but they were much *simpler*.
- Kepler tried to convince Galileo of this, but Galileo rudely blew him off.

Newton Brings it Home…

- In 1687, Isaac Newton published the "The Mathematical Principles of Natural Philosophy" in which he proposed the "universal law of gravitation", in which put forth his laws of motion, including.

Force $\vec{F} = m\vec{a}$ Acceleration

mass

- He then came up with the "universal law of gravitation", in which two massive bodies exert an attractive force proportional to the product of their masses divided by the square of the distance between them.

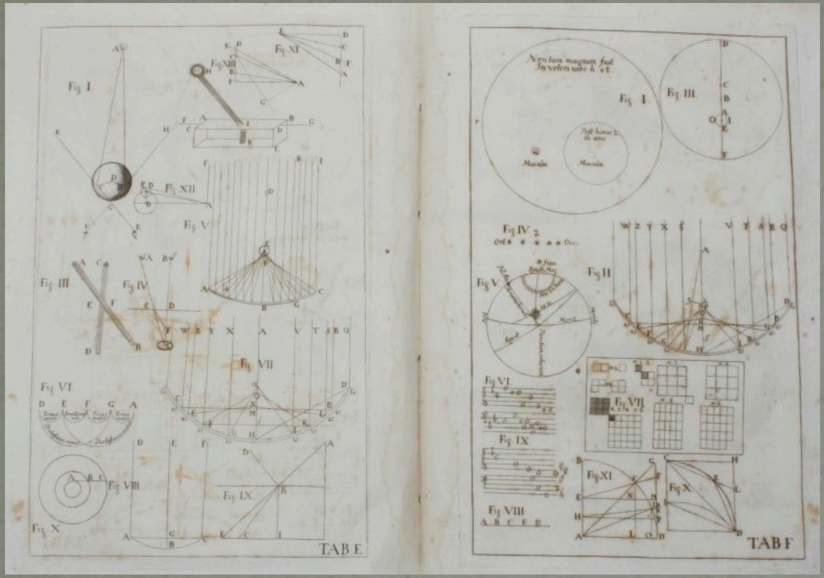
$$F = G\frac{m_1 m_2}{r^2}$$

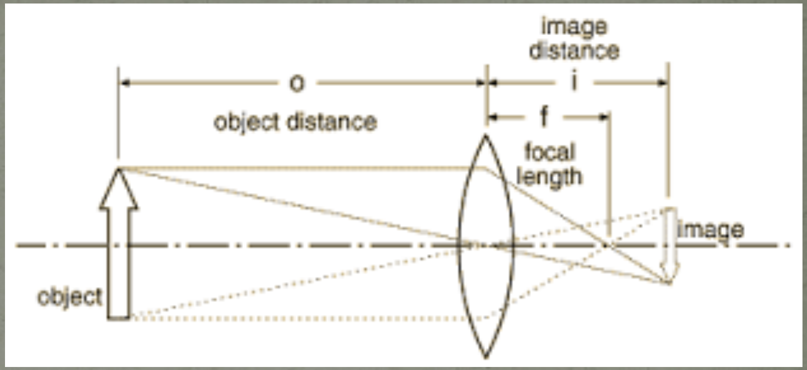
- This didn't have to explain all the planetary observations, it just had to predict Kepler's Laws, which it did (of course he had to invent calculus along the way.
- This was the true beginning of physics. Now on to light…

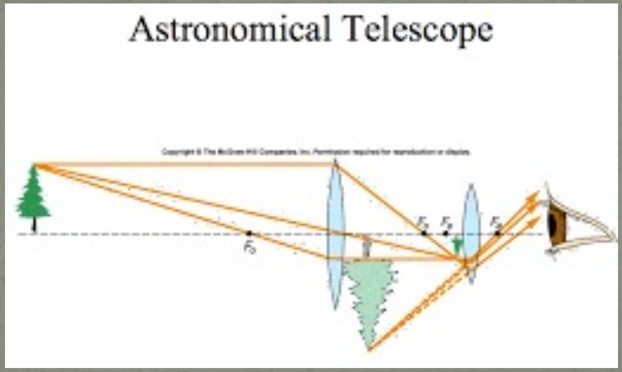
A (very!) Brief History of Light

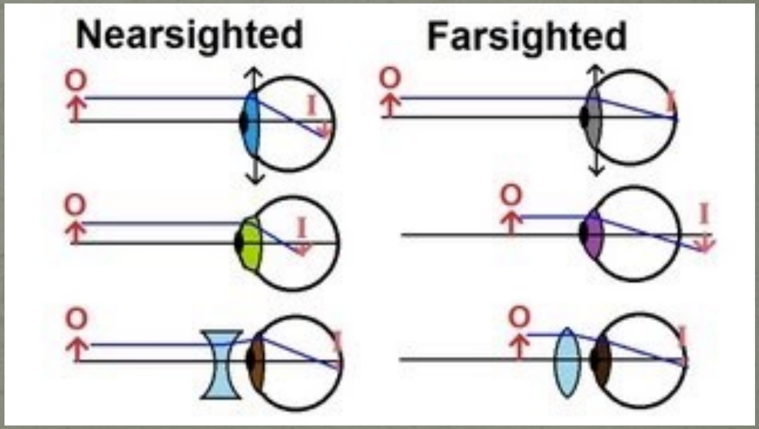
- 5th century BC: the Greek philosopher Empedocles postulated that light traveled in "rays" *from the eyes*, allowing us to see
  - Why can't we see in the dark?
- 3rd century BC: Euclid worked out ray-based theories of reflection, still assuming light rays came *from* the eye
  - although he did toy with the idea they might go in the other direction.
- 2nd century AD: Ptolomy extended Euclid's work to include refraction (bending of light).
- ~1000 AD: The Arab scientist Alhazen created the first fairly accurate model of vision (including the direction of light rays)
- ~1600 AD: German scientist Johannes Kepler invents modern optics and image formation, explaining how lenses, mirrors, telescopes, microscopes, etc. work.
  - He also tried to tell Galileo about this and got a nasty letter in response.

Keplerian Image Formation



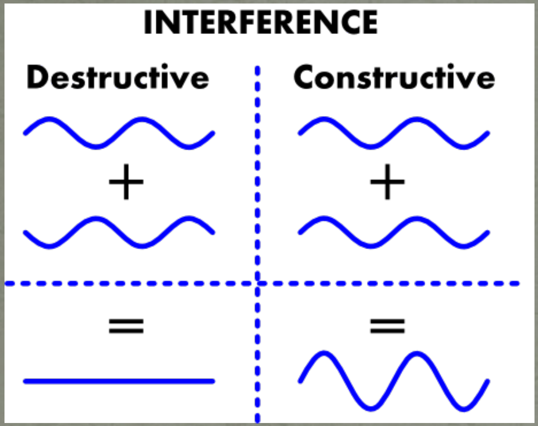




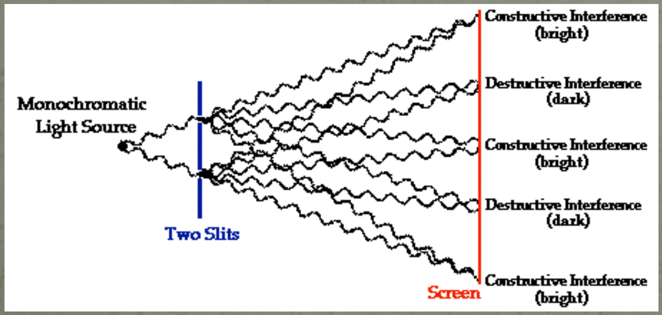


Nature of Light: Waves or Particles?

- People were divided over whether light "rays" consisted of particles ("corpuscular theory") or waves.
- If waves, then they should "interfere" (add or cancel out)

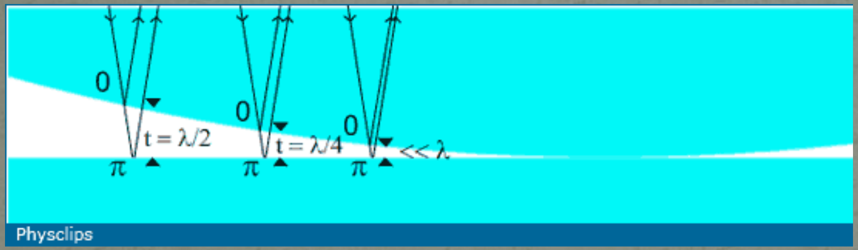


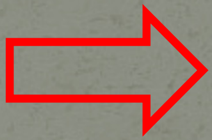
Example: Interference of waves on water



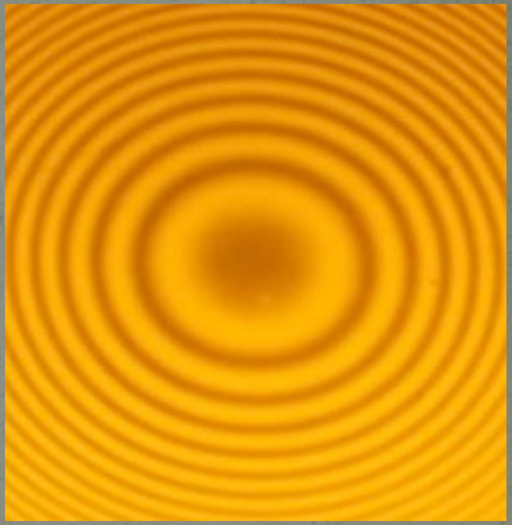
Newton's Rings

- Isaac Newton (who firmly believed light was a particle!) observed interference by placing a curved surface against a flat surface





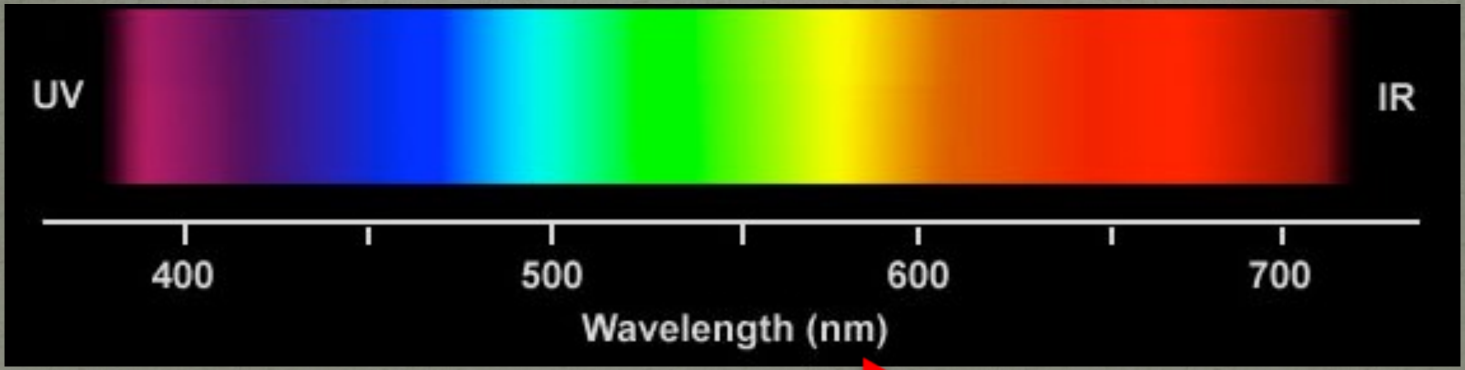
- These "Newton's Rings" were strong evidence that light is a wave!
- Can also calculate the wavelength.



Top View

Color and Wavelength

- Newton also observed that a prism split light into different colors
  - Hypothesized that different colors were different “corpuscles”
- In 1802, using interference techniques, Thomas Young determined that each color had unique wavelength



1 nanometer = 1 *billionth* of a meter

- The picture is starting to come together: reflection, refraction, image formation, color. What’s left?

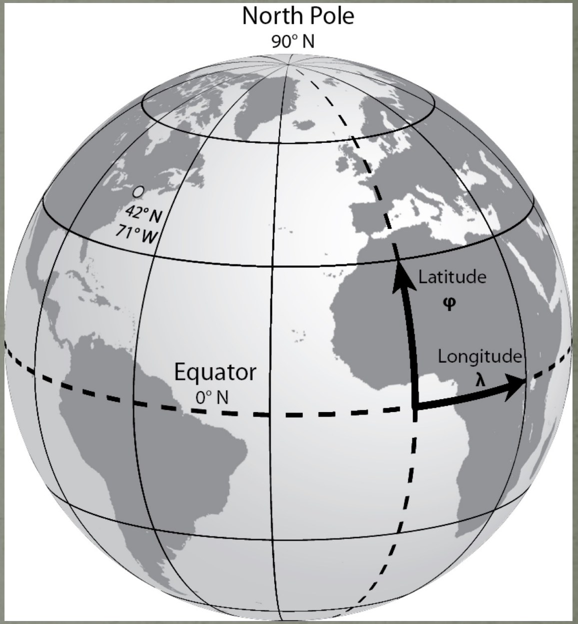
How fast does light move?

- Since the 5^{th} century BC, philosophers wondered how fast light moved.
- In the 17^{th} century, at least two attempts were made to measure the speed of light.
  - In 1629, Isaac Beeckman carried out an experiment in which looked for the time it took a cannon flash to reflect from a mirror a mile away.
  - Around 1638, Galileo (possibly) tried to measure the speed of light using two men with lanterns on distant hilltops

- Both men concluded that light was too fast to be measured in these simple ways.

Digression: Latitude and Longitude

- Our method of specifying a location on the Earth dates back at least to Eratosthenes, in the 3rd Century BC.
  - First person to measure the circumference of the Earth
- To measure latitude, all we need to do is measure the angle between the North Star and the horizon
- Because the earth is turning, in order to measure longitude, we need to know an angle to a star *and the absolute time*.
  - 1 minute = 16 miles at the Equator!



- This was THE BIG PROBLEM in navigation for several hundred years.
  - Caused many ships to get lost or run aground.
- Many governments offered big rewards to solve the problem.
- What the heck does this have to do with light?
  - Bear with me!

Maps and the New World

- By the 16th and 17th centuries, Old World maps were pretty accurate
- Elsewhere, latitude could be very precise, but longitude could be wildly off
- Now it mattered!
  - Ships had to navigate over large distances with no landmarks
  - Whole fleets ran aground
  - Governments offered rewards to solve the "longitude problem"

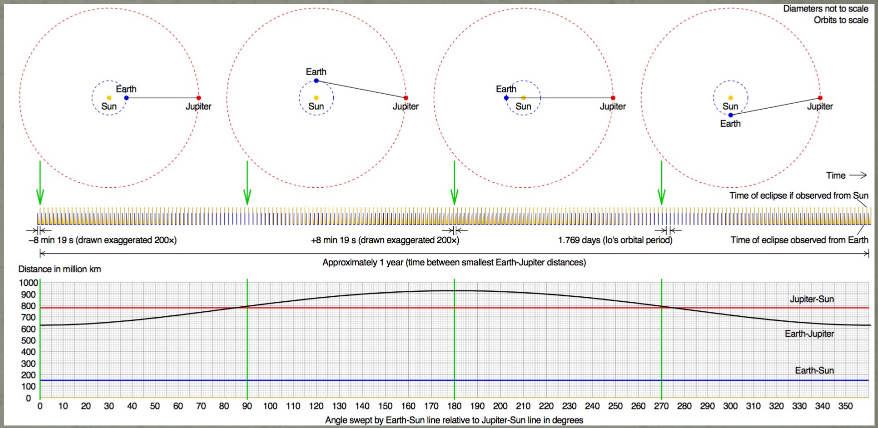
Willem Janszoon Blaeu, ~1630

Modern

- What does this have to do with light?

Rømer's Accidental Discovery

- People assumed that no clock could measure time so precisely, so it would have to be based on some sort of astronomical observation.
- In 1676, the Danish astronomer Ole Rømer was trying to win the "Longitude Prize", offered by King Phillip III of Spain, by observing the moons of Jupiter, as suggested by Galileo.
- He found that the period was shorter or longer depending on whether the Earth was approaching or receding from Jupiter, leading to a difference of around 20 minutes as the Earth went from one side of the sun to the other
  - Remember, 1 minute = 16 mile error in position at the Equator!



- He and Christian Huygens realized they could explain this if light had a finite speed, which they calculated to be about 135,000 miles per second
  - Correct answer: 186,000 miles per second
- Spoiler: the longitude problem was eventually solved with a clock, invented by John Harrison (see "Longitude" by Dava Sobel!)

Moving on: Another Happy Accident

- The 19th Century was the golden age of experimental physics, particularly experiments involving electricity and magnetism.
- By the second half of the century, scientists had learned
  - Electric fields are created by electric charges
  - Magnetic fields are created by moving charges
  - Electric fields can also be created by *changing* magnetic fields
    - This is how generators work

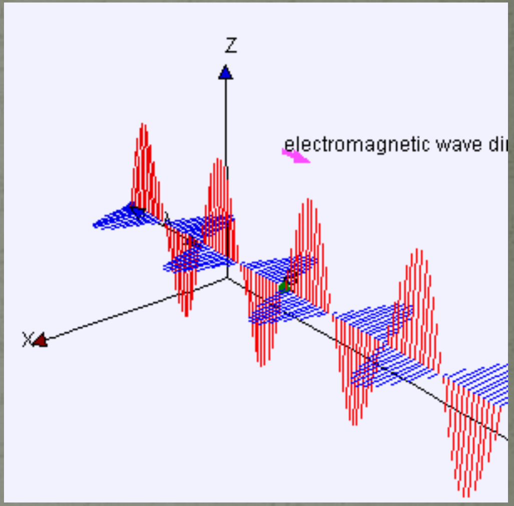
Maxwell's Equations

- In 1861, James Clerk Maxell attempted to collect everything that was known about Electricity and Magnetism into a single set of equations.
- He was *almost* able to express all of the existing experimental observations as a self-consistent set of mathematical equations
  - There was one (seemingly) small problem having to do with magnetic fields.
- For purely mathematical reasons, he added an extra term
  - In addition to electric currents, magnetic fields could be generated by *changing electric fields*.
- This turned out to have rather profound implications…

Electromagnetic Waves

- Before, it was believed that you needed electric charges to make an electric or magnetic field, but Maxwell's Equations showed you could have
  - (changing electric field)➔(changing magnetic field)➔ (changing electric field)➔

    "Electromagnetic Wave"

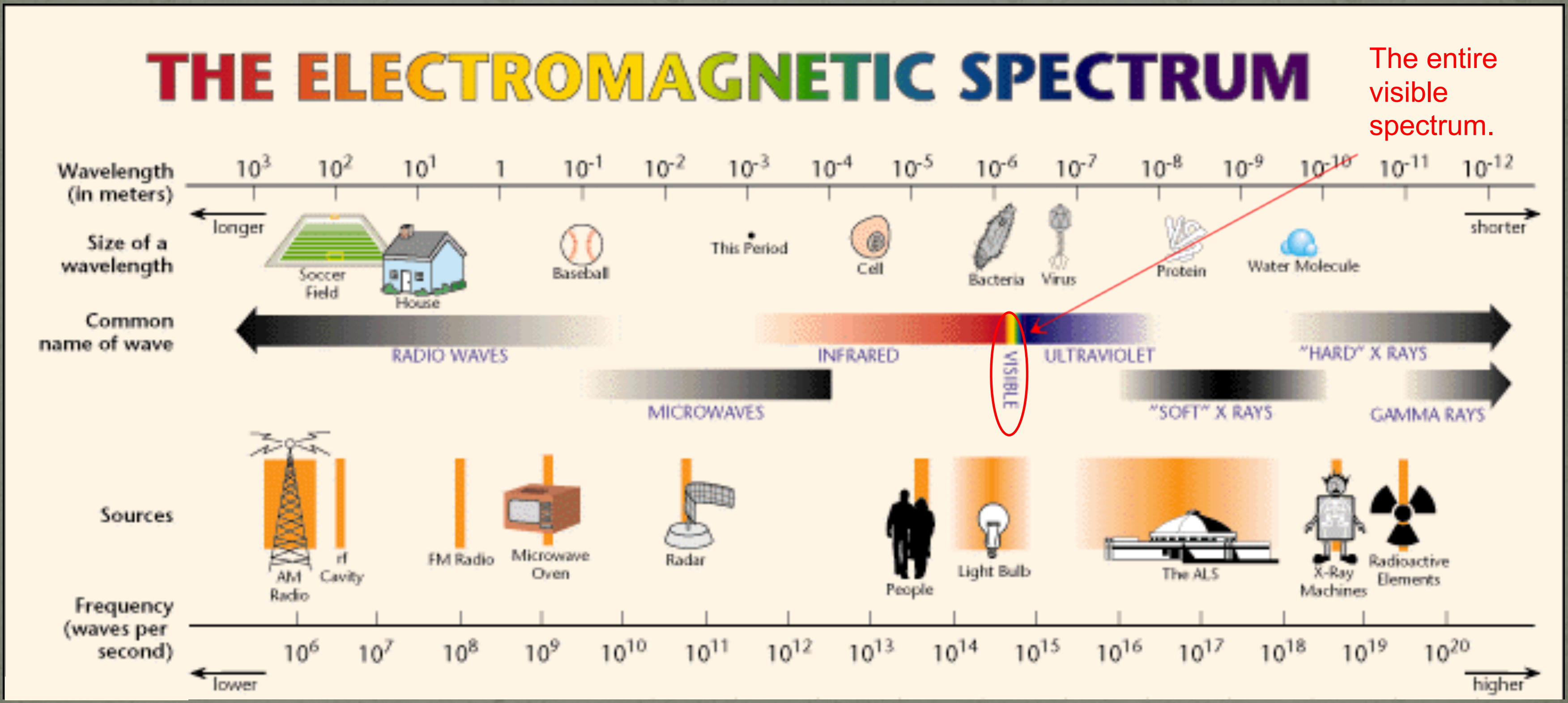


- What's more, Maxwell could calculate the velocity at which such a wave would travel
  - It exactly matched the speed of light!!!
- He wrote (with trembling hands, maybe?):

"we can scarcely avoid the inference that light consists in the transverse undulations of the same medium which is the cause of electric and magnetic phenomena"

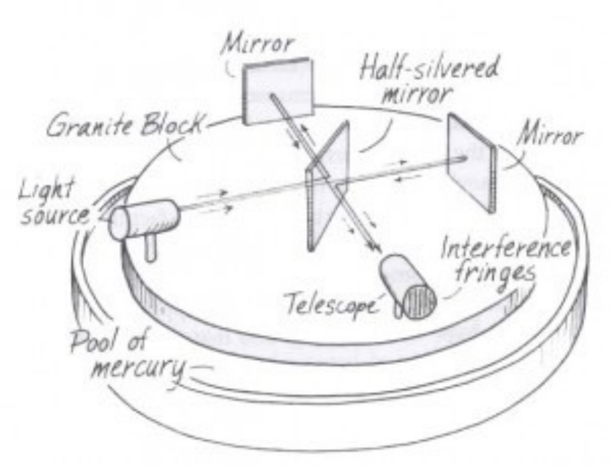
It's all the same thing…

- In one fell swoop, Maxwell not only unified electricity and magnetism, but his results would eventually show that light, heat, radio waves, x-rays, gamma rays, etc., are *all* really the same thing – differing only in wavelength!



What's "undulating"?

- As often happens science, one answer raised a lot more questions.
- All (other) known waves require a "medium" (air, water, earth, "the wave") to travel through.
- Light at least appears to travel through a vacuum.
- In science, always try the simplest answer first:
  - Maybe vacuum isn't really empty?
- Scientists hypothesized the existence of "luminiferous aether", and started to look for it…
  - The "Michelson-Morley Experiment" (1887) looked for difference in velocity based on whether a beam was traveling along the direction of the Earth's motion or transvers to it: no effect found!



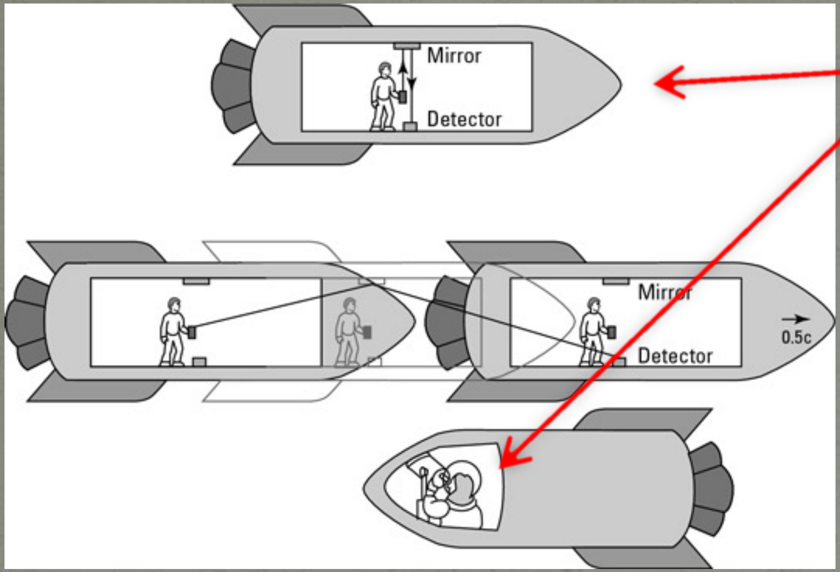
- Biggest mystery in science for 20 years!

Einstein to the Rescue

- In 1905, Albert Einstein postulated that perhaps the equations meant exactly what they appeared to mean:
  - The speed of light was the same *in any frame* in which is was measured.
- He showed that this could "work", but only if you gave up the notion of fixed time.
  - ➔ "Special Theory of Relativity"
- Profound implications…

Example: Time Dilation

- Einstein said, “The speed of light must be the same in any reference frame”. For example, the time it takes light to bounce off a mirror in a spaceship must be the same whether it’s measured by someone in the spaceship, or someone outside of the spaceship.

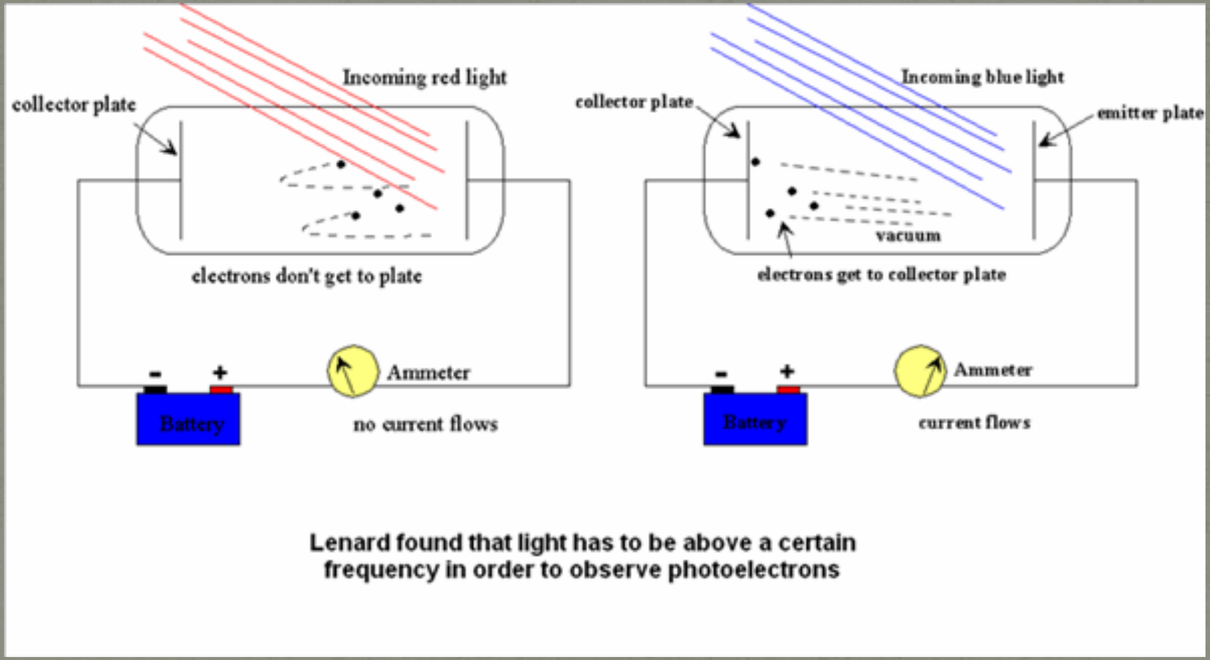


- These two people have to measure *the same* speed for light, even though light is traveling a different distance for the two of them.
- The only solution? More time passes for the stationary observer than the guy in the spaceship!
  - “Twin Paradox”

- This seems weird, but it applies to everything we with, eg, accelerators
  - Example: the faster pions and muons move, the longer they live.

Now we're done, right?

- Well….
- Around the turn of the last century, Philipp Lenard observed the "photoelectric effect":
  - light could knock electrons out of material and create an electric current, but their energy depended only on the *color*, not the intensity.



- This really had people scratching their heads!

Einstein to the rescue (again)

- The same year he proposed the Theory of Relativity, Einstein suggested a new theory for light
  - Really, at this point, he was just showing off
- He hypothesized that light consisted of "packets", each with an energy that depended on its wavelength:

Planck's Constant

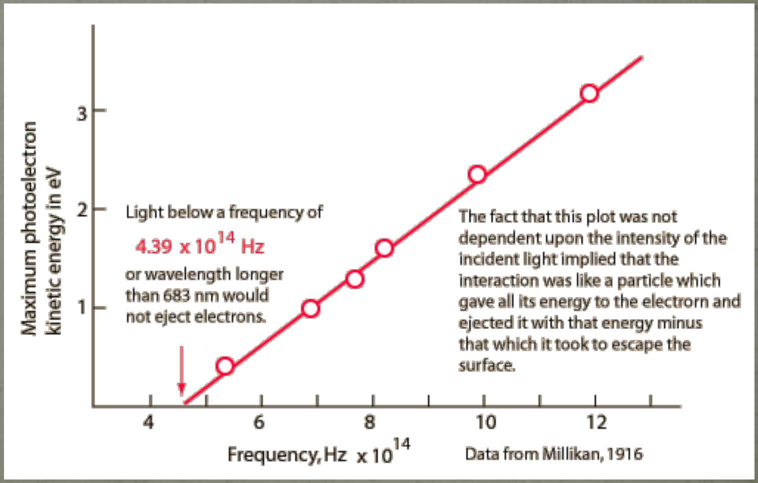
Speed of light

Energy

$$E = \frac{hc}{\lambda}$$

Wavelength

- Shorter wavelengths have higher energy, and can therefore kick out electrons with higher energy.



Wait! What the what?

- I thought we had that whole particle/wave thing worked out after the discovery of interference, right?
- Now Einstein was saying light was a particle again.
- How could light be both a particle *and* a wave?
- This question obsessed the best minds in the world for decades (and still does, really)
- Over time, a working theory emerged, known as “quantum mechanics”

…and it’s really kind of weird!

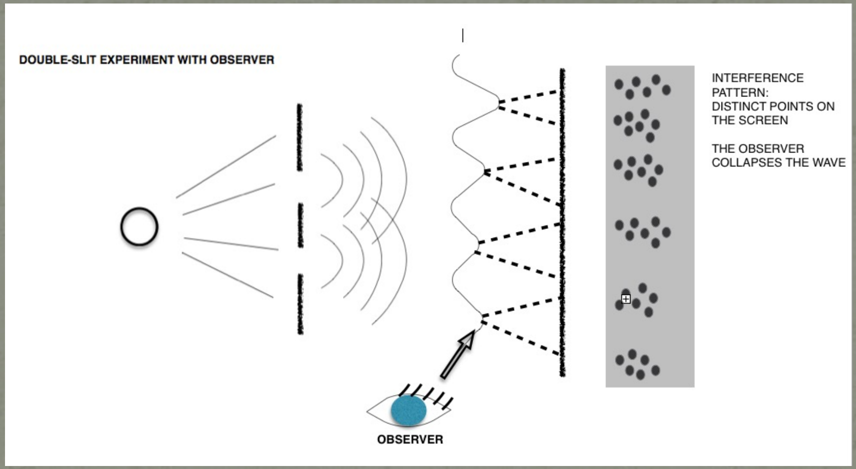
Quantum Mechanics

- Light (and everything else) has a wavelength, which depends on its momentum

$$\lambda = \frac{h}{p}$$

Momentum

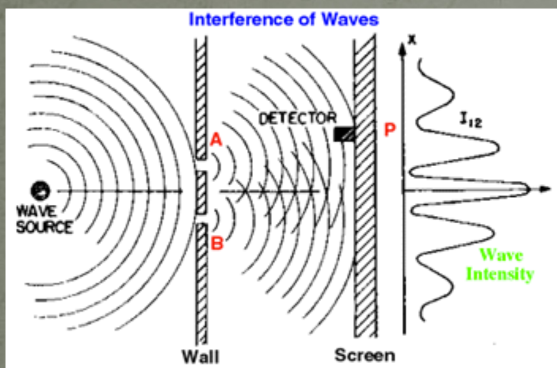
- Particles propagate (and interfere!) as waves, but they are observed (interact) discretely, with a *probability* that depends on their amplitude.



- At the smallest scales, everything is governed by random chance, and this introduces a fundamental uncertainty into our ability to measure things.

Example: Quantum Two-Slit Interference

Phosphor screen detects single photons
from low intensity light source

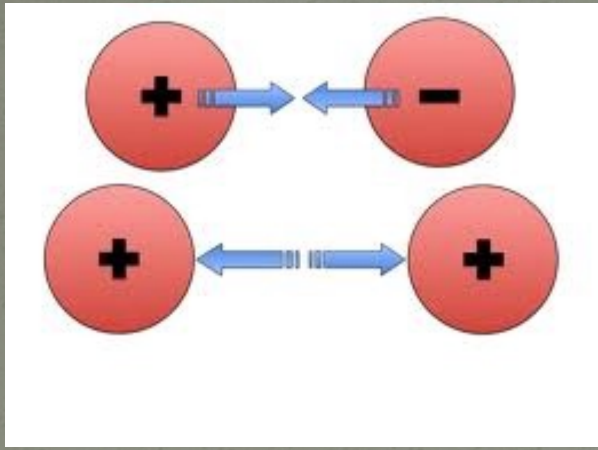


When they add up, we see the interference pattern.

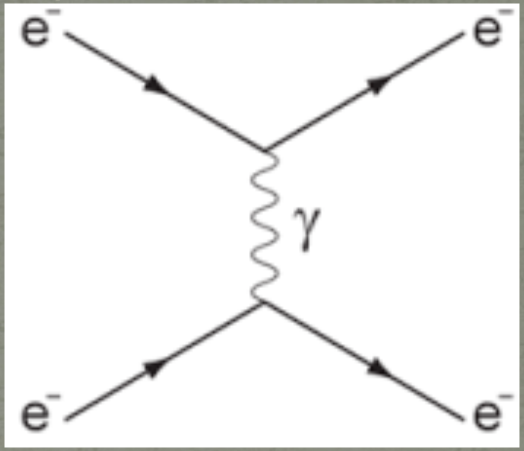
Quantum Electrodynamics (QED)

- Based on the work of Richard Feynman and others, we now view the electric field as the discrete exchange of photons.

Classical picture: charged particles produce "fields", which exert forces on other particles



Quantum picture: charged particles have a probability of exchanging "virtual photons"

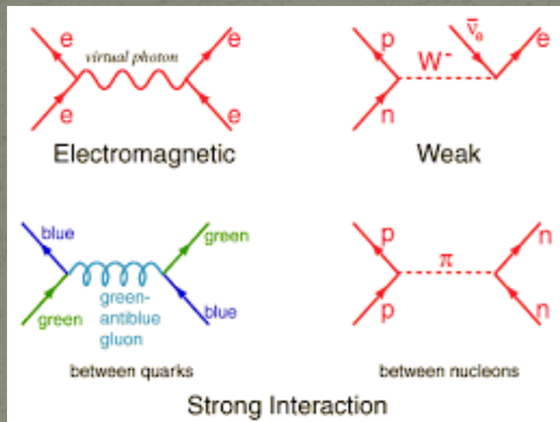


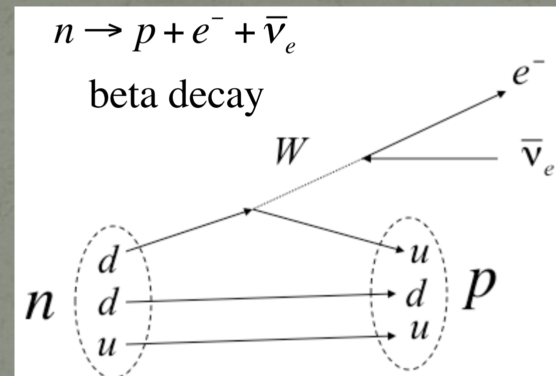
"Feynman Diagram"

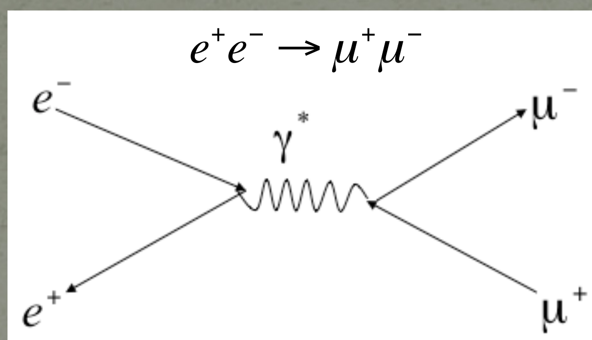
- If the probability is high enough, you exchange a lot of photons and quantum ➔ classical again.

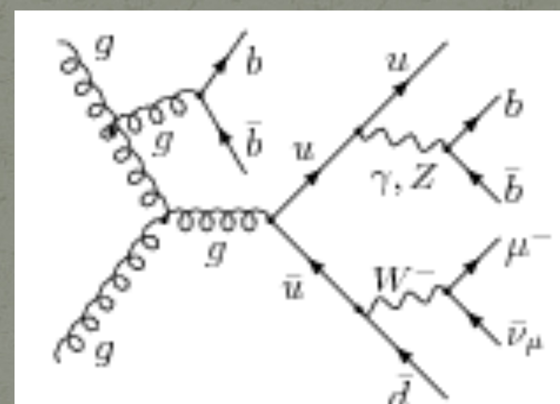
The Rest is History…

- This formalism became the model for how we treat all forces









- They're literally the basis of everything we do in fundamental physics

Summary: The "Light" in Your Smart Phone…

- Processor/circuits
  - Fabrication
    - Classical optics (lithography)
    - Photoelectric effect
  - Operation
    - Quantum mechanics
  - Heat dissipation
    - Radiant heat theory
- LCD Screen
  - Quantum mechanics
- Camera
  - Lens
    - Classical optics
  - CCD
    - Photoelectric effect
- Phone and wireless signals
  - Electrodynamics

- GPS
  - Atomic clocks
    - quantum mechanics
  - Signals
    - electrodynamics
  - Corrections
    - Special and General relativity

Backup Slides

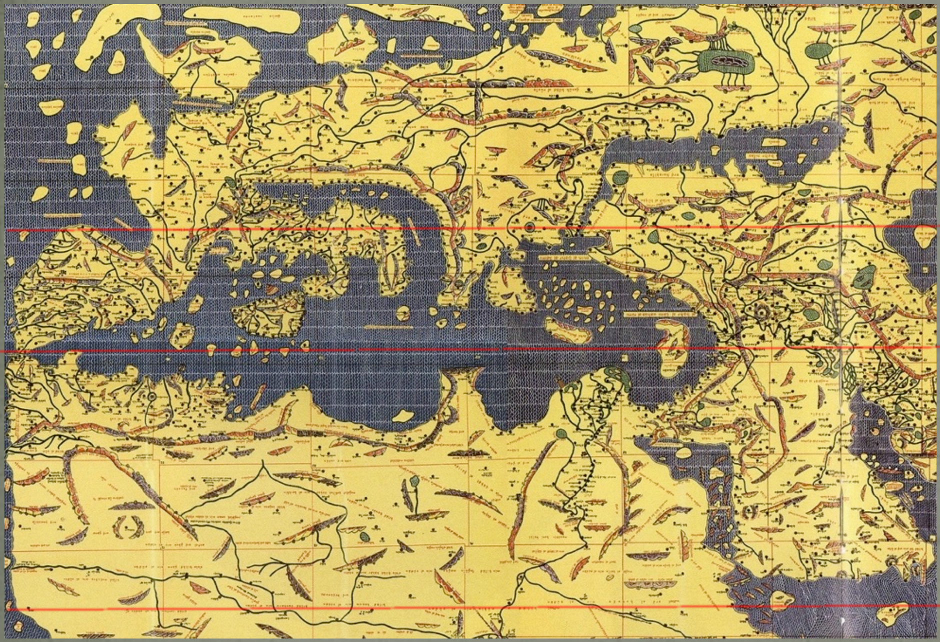
Backup slides

Outline

- The basics (easy stuff)
  - Reflection
  - Refraction
  - Ray tracing and images
  - Interference
- Big surprises (hard stuff)
  - Speed of light
  - Electricity and Magnetism
  - Theory of Relativity
  - Quantum Mechanics and Quantum Electrodynamics
- What this teaches us about how science is done
- How this relates to what we do here

Maps

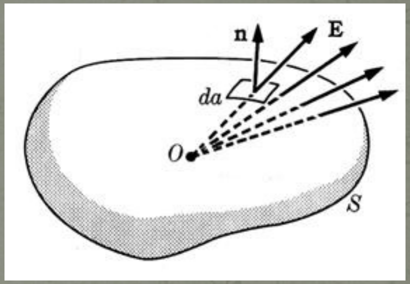
- Latitude was determined by stars
  - Pretty Accurate
- Longitude was determined by dead reckoning
  - Often way off



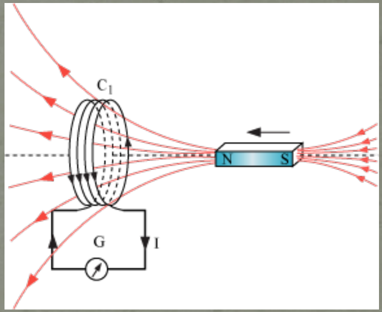
"Tabula Rogeriana" Muhammed al-Idrisi, 1154
(North was originally down)

Maxwell's Equation's

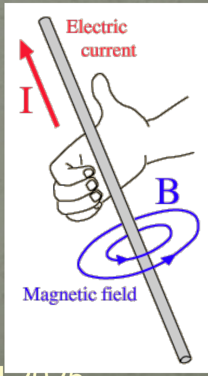
- In 1861, James Clerk Maxell attempted to collect everything that was known about Electricity and Magnetism into a single set of equations.
- Coulomb's Law:
  - The electric field *passing through a surface* depends on the charge contained by that surface



- Faraday's Law:
  - The electric field around a closed path depends on the *rate of change* of a magnetic field passing through the path.

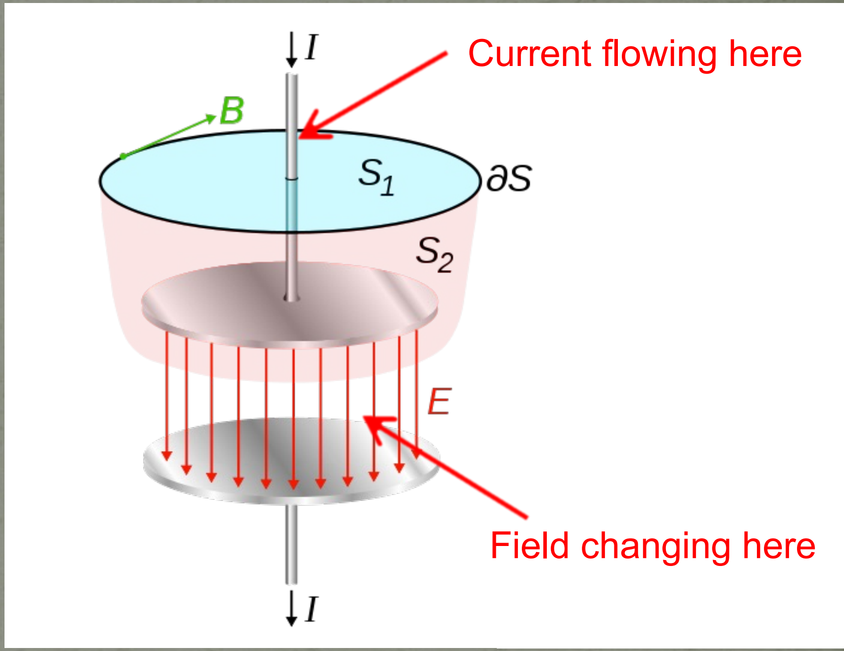


- Ampere's Law:
  - The magnetic field around a closed path depends on the electric current (flowing charge) passing through the path



Displacement Current

- There was a problem with Ampere's Law
  - Because electrical current can be blocked, there is no unique definition of the current passing *through* a loop.
- Maxwell had a "fix"
  - Any interruption in electric current causes a *changing* electric field.
- For *purely mathematical* reasons, Maxell hypothesized that a magnetic field could be created by an electric current *or* a changing electric field.



- This didn't affect a single measurement that had been made until that point, but it had profound implications.

Implications of Quantum Mechanics

- At the smallest scales, things occur randomly. We can talk about probabilities, but not certainties.
- The act of "observing" is never passive.
  - Example: we see because a photon hits the retina of our eye, causing a quantum transition.
- The fact that observation requires interaction introduces a fundamental uncertainty into our ability to measure things.

The Quest for Longitude

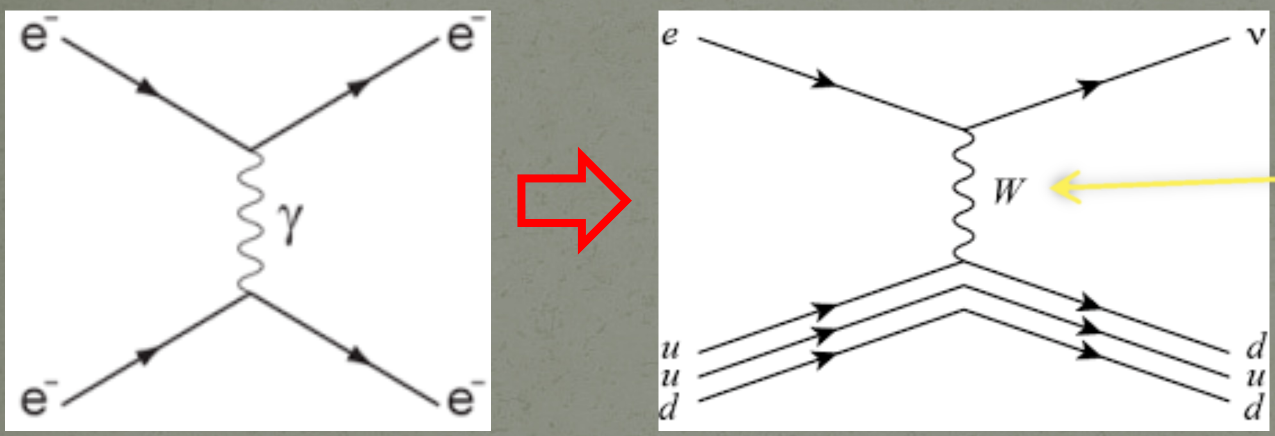
- By the 17th century, longitude was THE big problem for navigation.
- Numerous governments offered large prizes to the first person who could reliably determine longitude (ie, measure absolute time) over large distances.
- Many believed that such accuracy could *never* be achieved with a mechanical clock, and would have to rely on some celestial reference.
- This drove a period of intense advancement in observational astronomy
  - spoiler alert: John Harrison eventually solved the problem with a clock*

*see "Longitude" by Dava Sobel

The Rest is History…

- QED became the basis for our models of the other forces.
  - In quantum mechanics, a "force" is something that changes the "state" of a particle, which can sometimes mean changing it into another particle.

QED **Weak Interaction**



- And that's just the beginning…

Michelson-Morley Experiment

- If aether exists, then it must fill space and the earth must be passing through it.
- Light traveling along the direction of the Earth's motion should have a *slightly different* wavelength than light traveling transverse to it.
- In 1887, Albert Michelson and Edward Morley performed a sensitive experiment to measure this difference.
- Their result:
  - No difference ➔ no aether!
- Biggest mystery in science for almost 20 years.