Enlightened:
Some things we've Learned by Studying Light

Eric Prebys
Fermilab

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. I'll focus on this
- 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

Outline

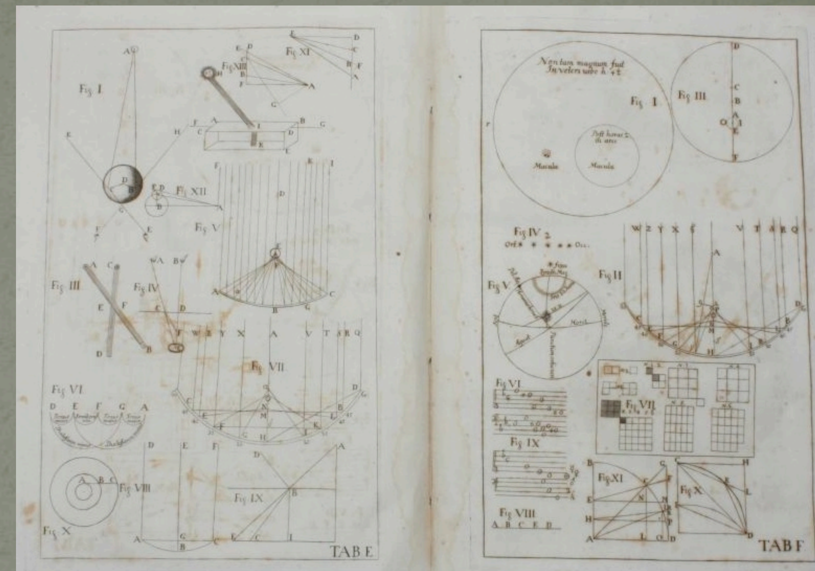
- The basics (easy stuff)
  - Reflection
  - Refraction
  - Ray tracing and images
  - Interference
- Big surprises (hard stuff)
  - Speed of light
  - Electricity and Magnetism
  - Theory of Relativity
  - Quantum Mechanics and Quantum Electrodynamics
- What this teaches us about how science is done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

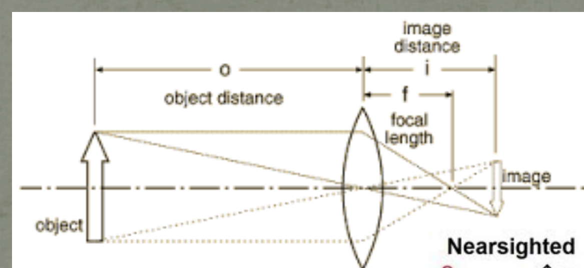
A (very!) Brief History of Light

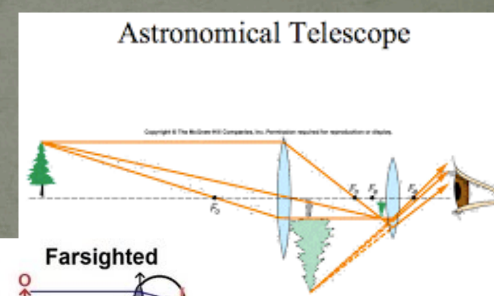
- 5th century BC: the Greek philosopher Empedocles postulated that light traveled in "rays" *from the eyes*, allowing us to see
  - Why can't we see in the dark?
- 4th century BC: Aristotle argues that light rays originate from the object,
  - His theory isn't very quantitative, and doesn't really catch on.
- 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.

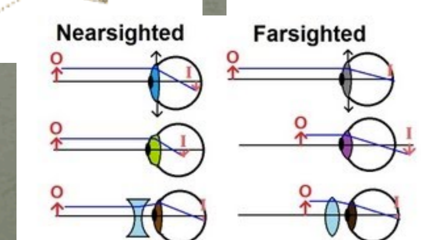
Keplerian Image Formation

- In “Astronomiae Pars Optica” (1604), Kepler explained image formation in terms refraction, reflection, and “ray tracing”.
- Led to significantly improved telescopes!
- To this day, Kepler’s “geometric optics” is the basis of our understanding of:
  - mirrors
  - telescopes
  - microscopes
  - cameras
  - eyeglasses
  - etc…



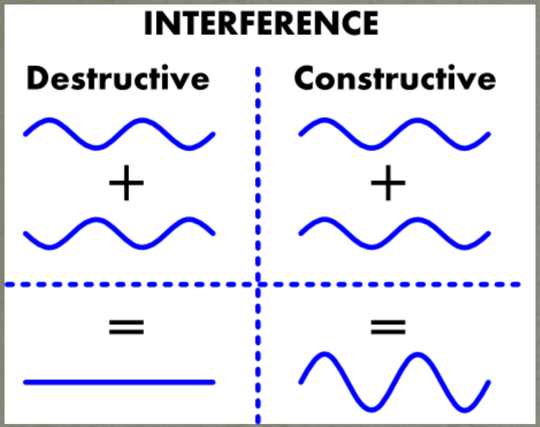


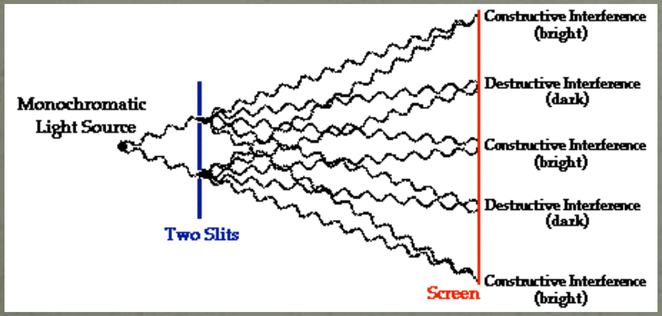




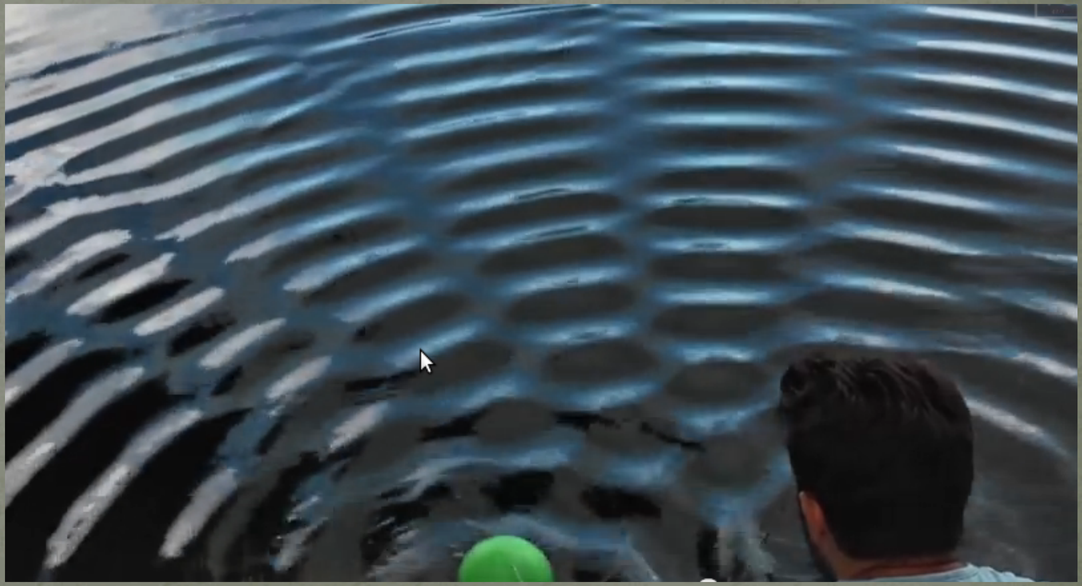
Nature of Light: Waves or Particles?

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



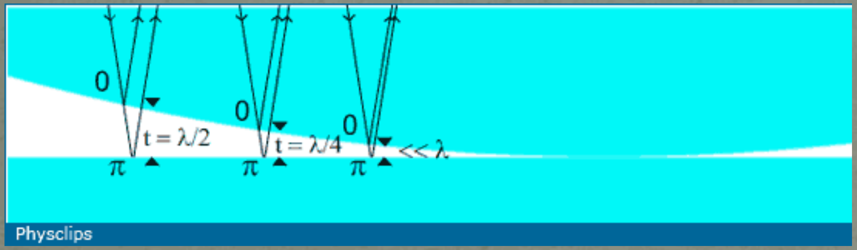


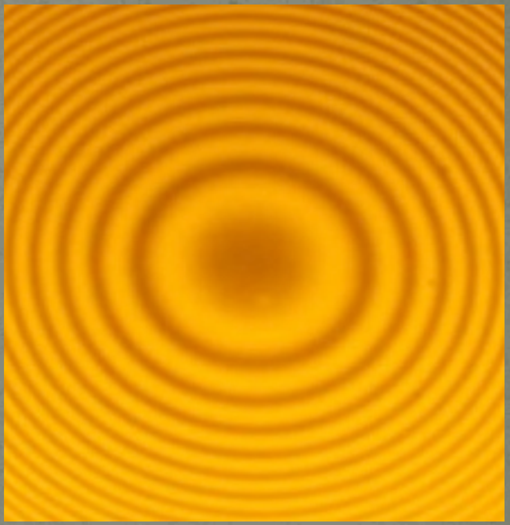
Example: Interference of waves on water



Newton's Rings

- Since we don't see obvious signs of interference, light waves, if they exist, must be very small, and we would need small scale geometries to see them.
- Newton (who firmly believed light was a particle!) observed interference by placing a curved surface against a flat surface



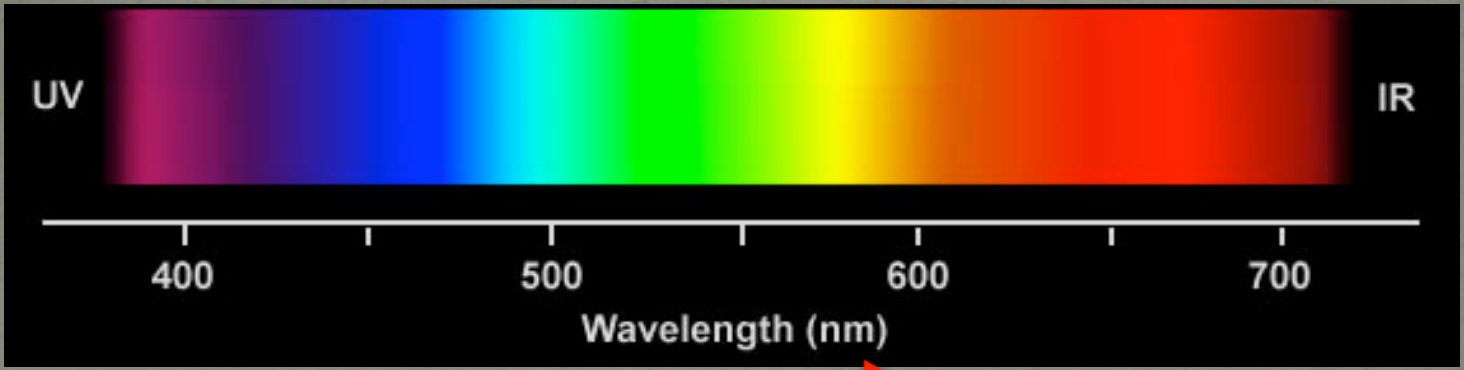


Top View

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

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?

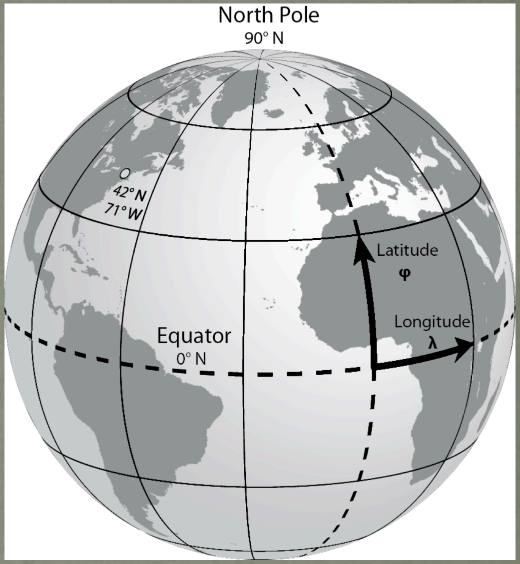
How fast does light move?

- In the 5th century BC, the Greek philosopher Empedicles suggested that light might move with finite velocity
  - Remember, he thought light went from our eyes to objects
- Aristotle believe that light traveled instantly, and his view held for almost 2,000 years.
- In the 17th 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



- The North Pole always points in the same direction, so *latitude* maybe measured anywhere on Earth using the apparent angle of the sun or stars, however
- Because the Earth is spinning, I need both angles *and absolute time* to measure longitude
  - If I know it's high noon in London, the angle of the sun with the horizon tells me my local longitude
  - At the equator, a *1 minute* error in time is a *16 mile* error in position!
- For centuries, longitude was determined by dead reckoning and (eventually) the time between a solar eclipse and local sunset.
- What the heck does this have to do with the speed of light?
  - Bear with me…

Maps and the New World

- By the 16th and 17th centuries, Old World maps were pretty accurate
- In the New World, latitude could be very precise, but longitude could be wildly off
- Now it mattered!
  - Ships had to navigate over large distances with no landmarks

Willem Janszoon Blaeu, ~1630

Modern

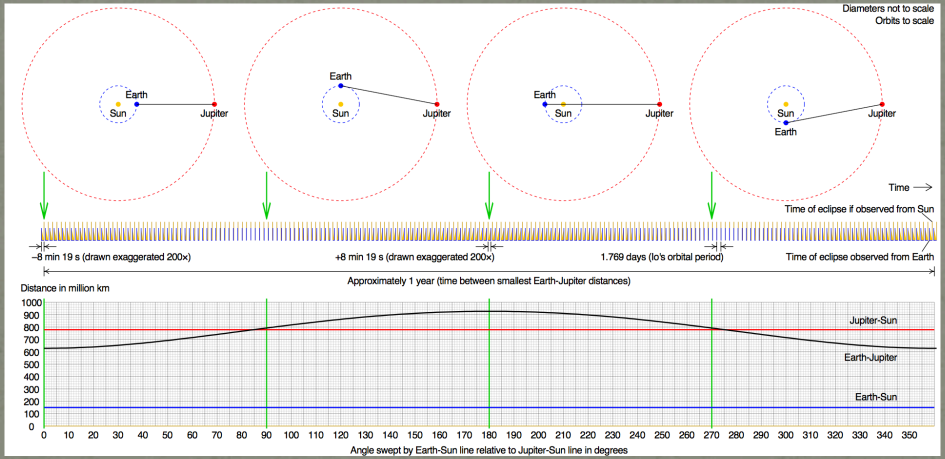
The Quest for Longitude

- 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

Rømer's Accidental Discovery

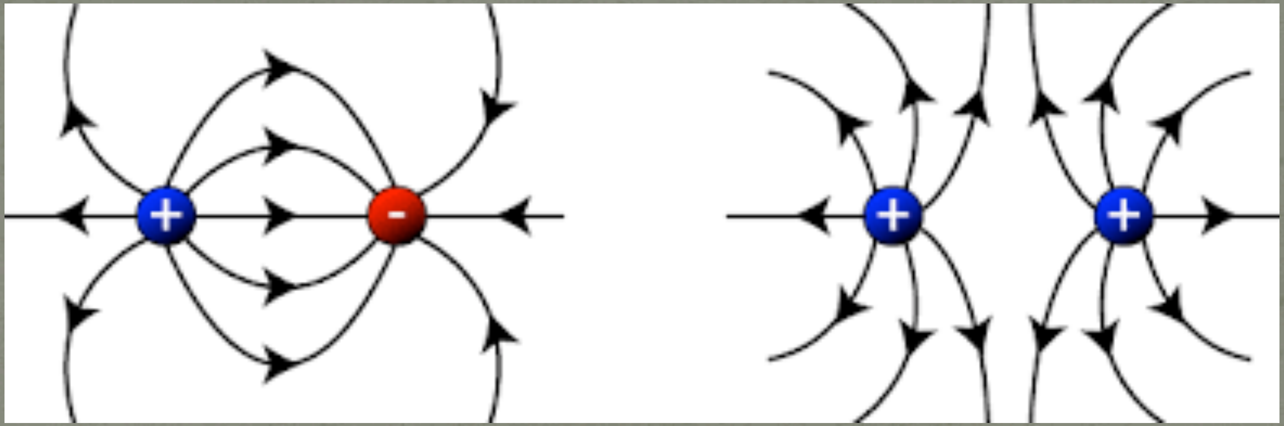
- The Danish astronomer Ole Rømer was trying to win the "Longitude Prize", offered by King Phillip III of Spain.
- Using a technique suggested by Galileo, he tried to use the period of Jupiter's moon Io as a clock, starting observations in about 1668
- He found that the period was shorter or longer depending 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 realized that he could explain this if light took 22 minutes to cross the diameter of the Earth's orbit around the sun, and he and Christian Huygens calculated the speed of light to be about 135,000 miles per second
  - Correct answer: 186,000 miles per second

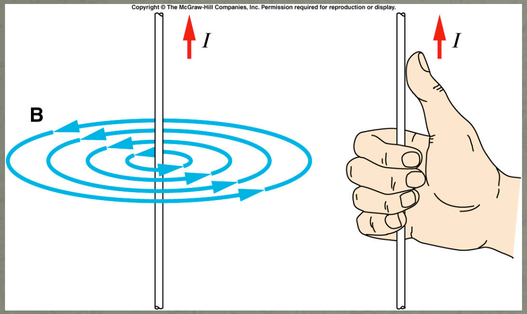
Moving on: Another Happy Accident

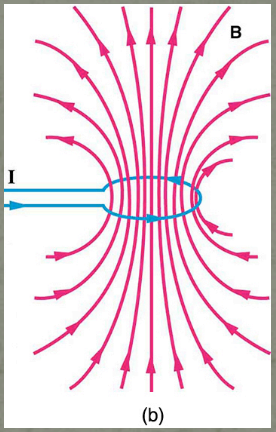
- The 19th Century was the golden age of experimental physics, at least as far as electricity and magnetism were concerned.
- By the second half of the century, scientists had learned
  - Electric fields are created by electric charges

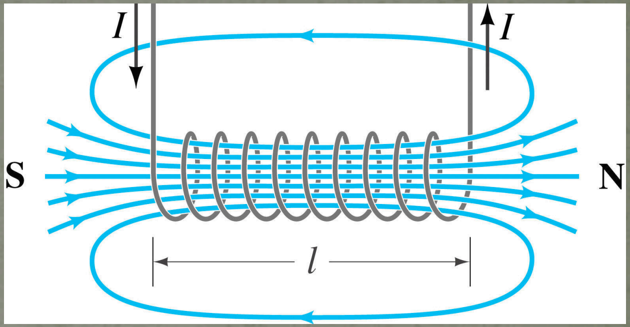


A Happy Accident (cont'd)

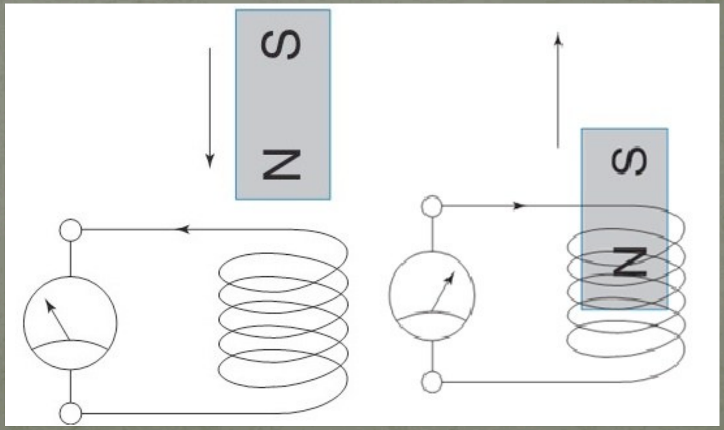
- They also knew
  - Magnetic fields are created by *moving* electric charges (electric current)







  - Electric fields can also be induced by *changing* magnetic fields
    - This is how a generator works



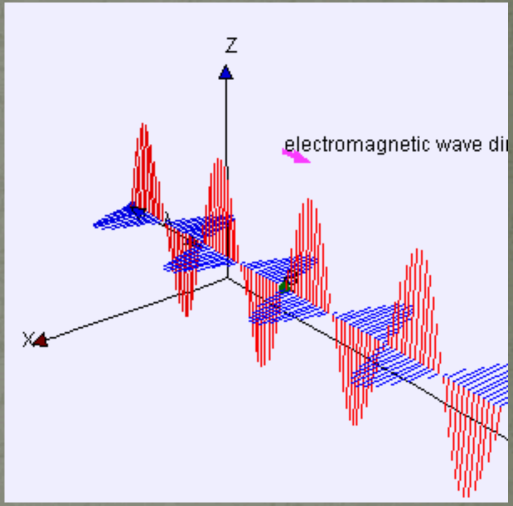
Maxwell's Equations

- 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!!!

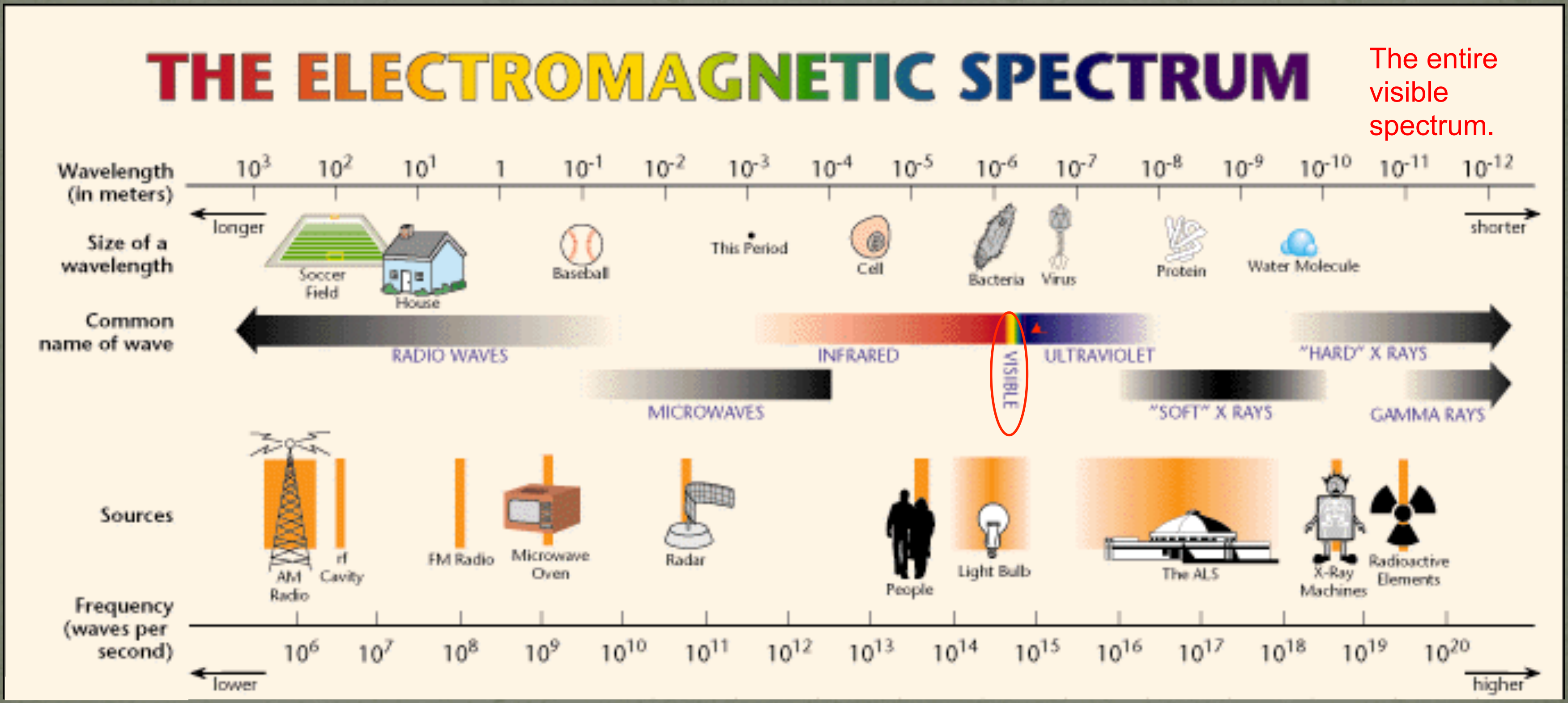


- He wrote (with trembling hands, maybe?):

"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!

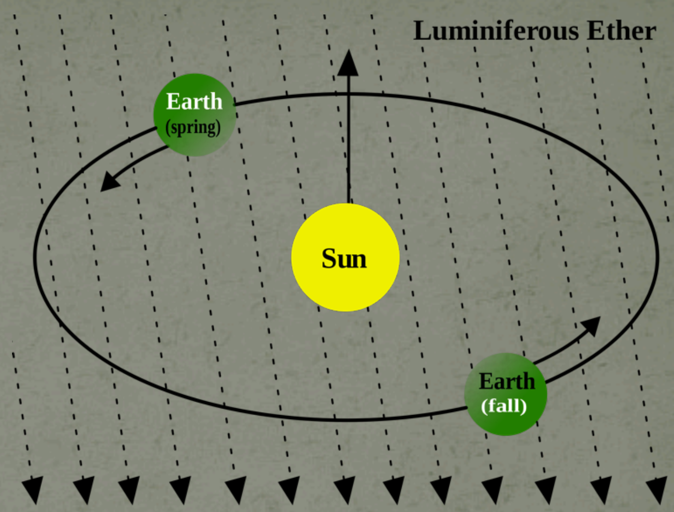


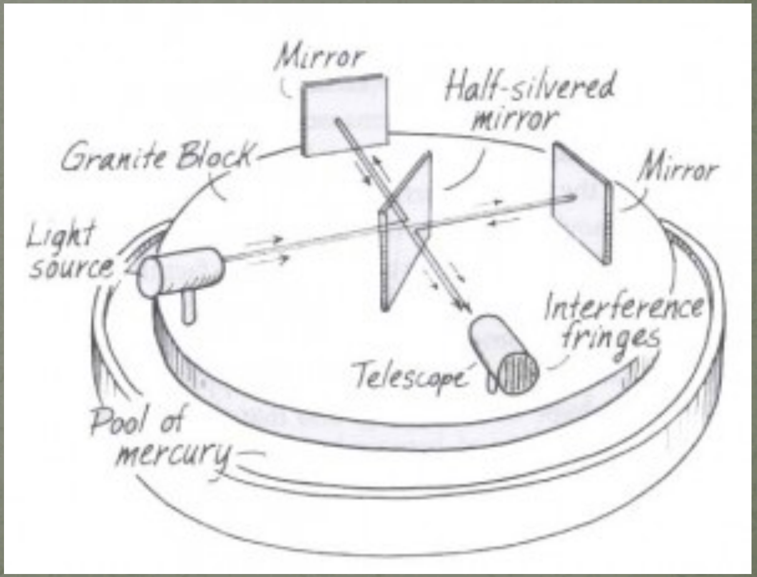
What's "undulating"?

- 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…

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.



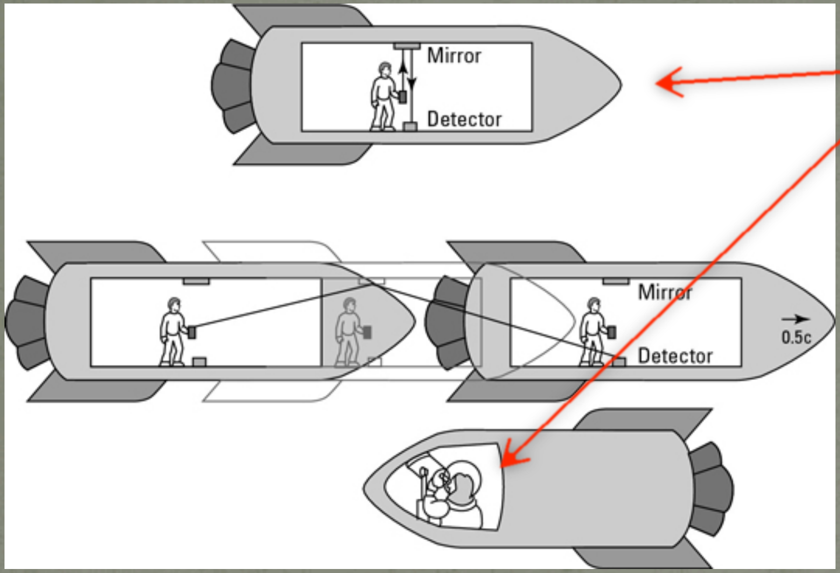


Einstein to the Rescue

- 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.

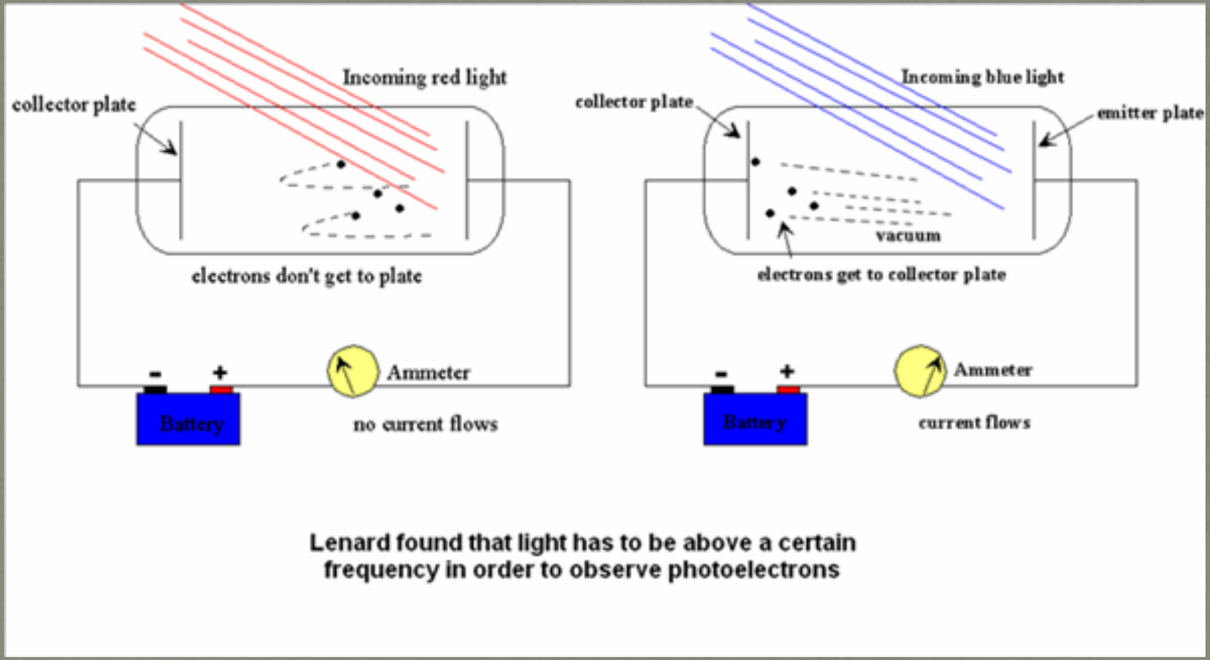


- These two people have to measure *the same* speed for light, even though light is traveling a different distance for the two of them.
- The only solution? More time passes for the stationary observer than the guy in the spaceship!
  - "Twin Paradox"

- This seems weird, but it applies to everything we do at the lab
  - 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

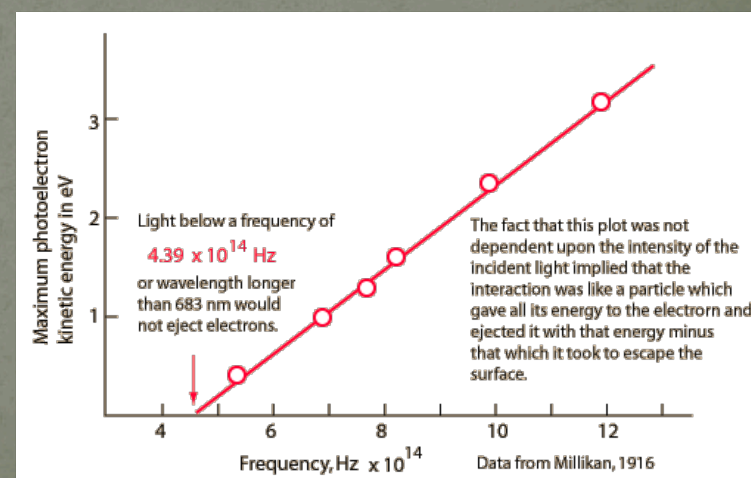
Speed of light

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!

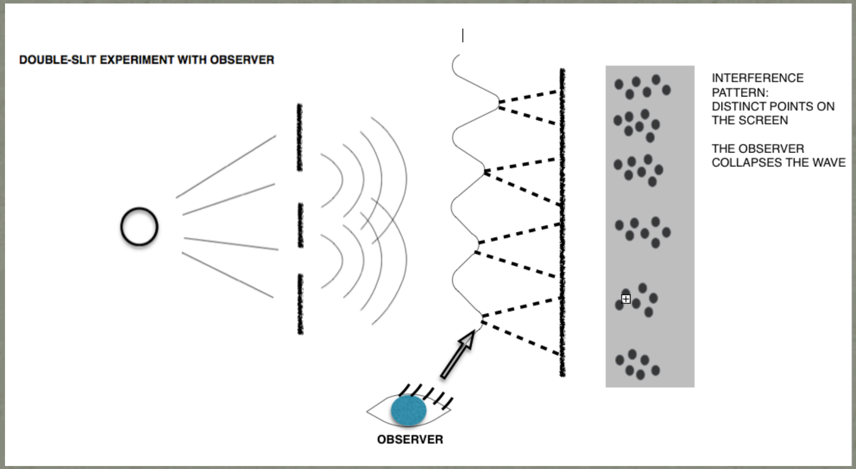
Quantum Mechanics

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

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

Momentum

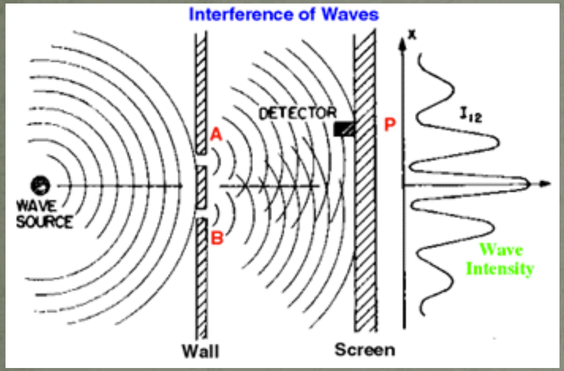
- Particles propagate (and interfere!) as waves, but they are observed (interact) discretely, with a *probability* that depends on their amplitude.



- 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

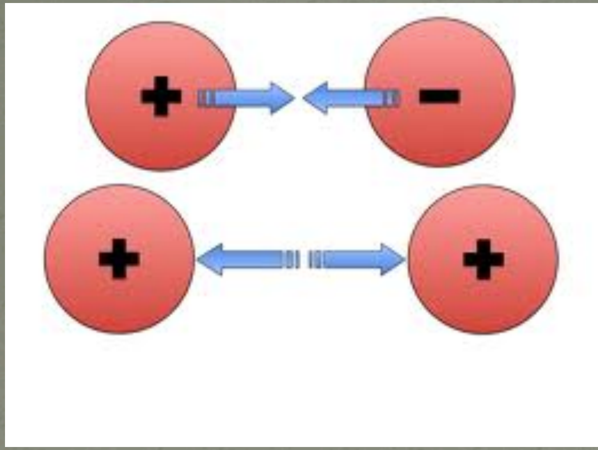


When they add up, we see the interference pattern.

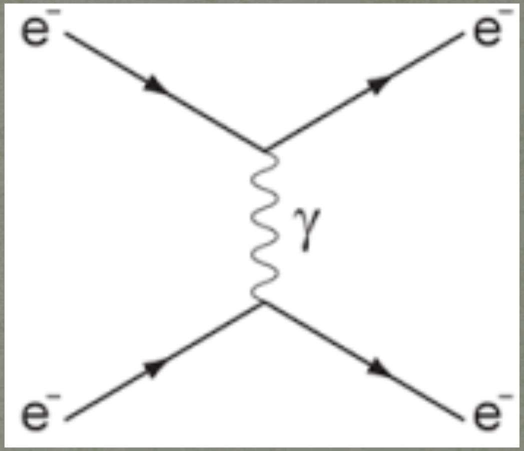
Quantum Electrodynamics (QED)

- 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"



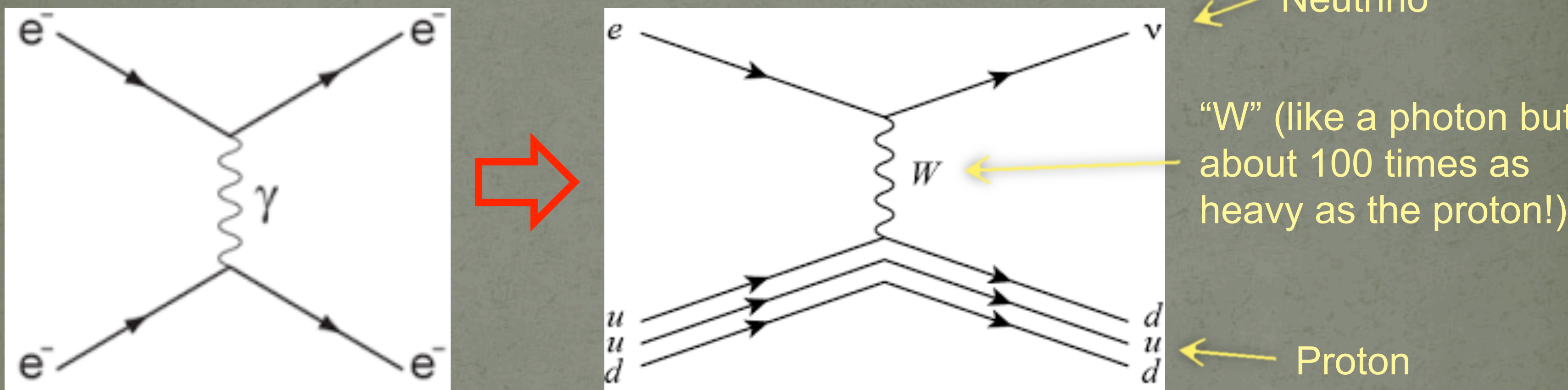
"Feynman Diagram"

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

The Rest is History…

- 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.

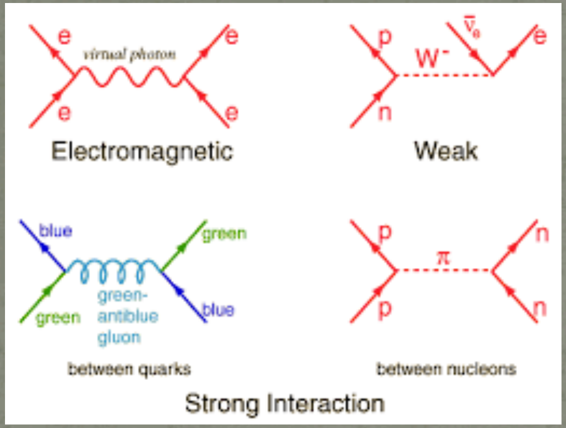
QED **Weak Interaction**

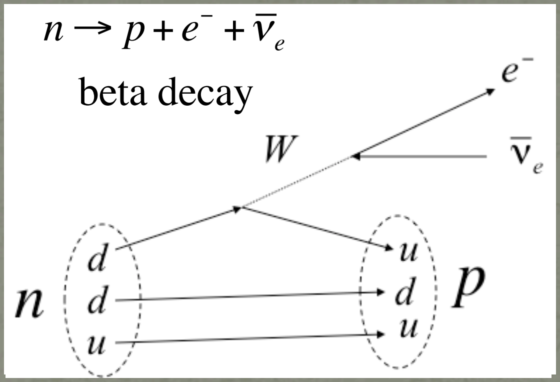


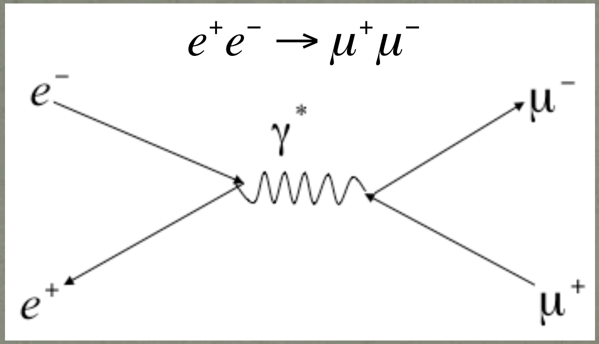
- And that’s just the beginning…

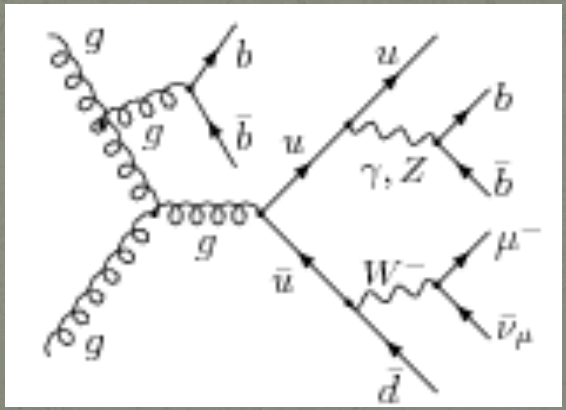
The Standard Model

- We can generalize these Feynman Diagrams and change their orientation to explain every type of particle interaction there is









- They're literally the basis of everything we do here.

Summary: Consider the 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

Acknowledgements

- Fermilab, for encouraging outreach
- Wikipedia and Google (of course)
- You, for sitting inside instead of shopping!

Backup slides

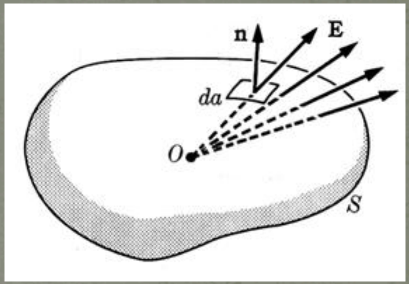
Maps

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

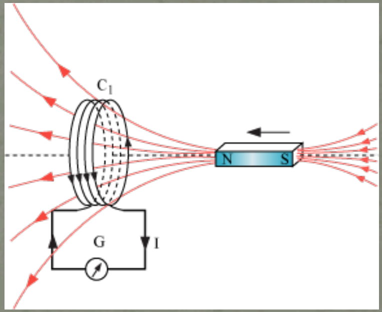
“Tabula Rogeriana” Muhammed al-Idrisi, 1154
(North was originally down)

Maxwell's Equation's

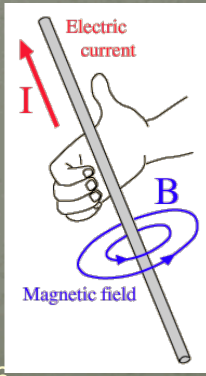
- In 1861, James Clerk Maxell attempted to collect everything that was known about Electricity and Magnetism into a single set of equations.
- Coulomb's Law:
  - The electric field *passing through a surface* depends on the charge contained by that surface



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

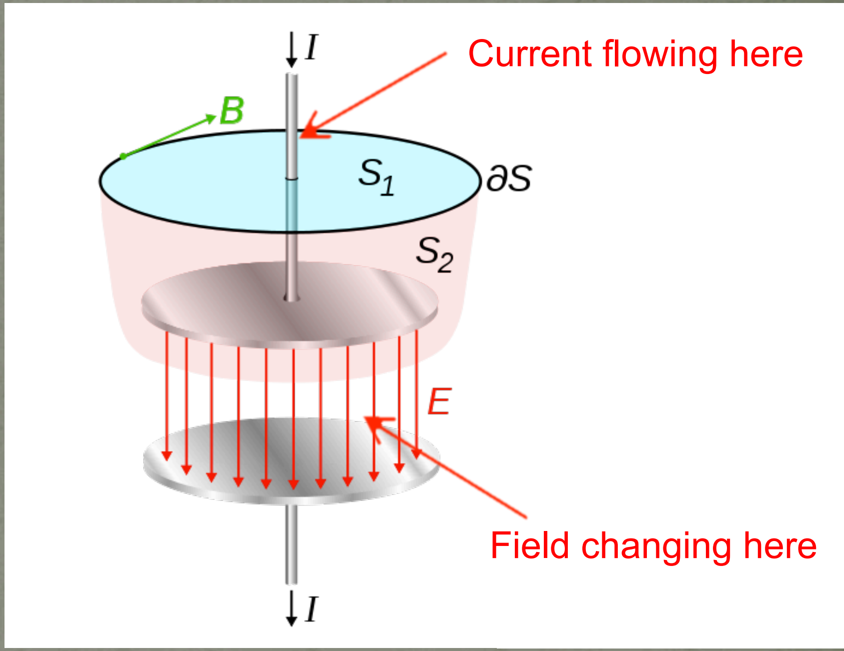


- Ampere's Law:
  - The magnetic field around a closed path depends on the electric current (flowing charge) passing through the path



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.