Lecture 18 Review: E&M, Relativity

Finishing Classical Physics: Waves, E&M
The First Revolution of the 20th Century: Relativity

Faraday

$\vec{E}$ & $\vec{B}$

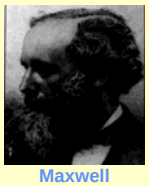
Action at a Distance?

Michelson-Morley Experiment

$v = f\lambda$

Ether?

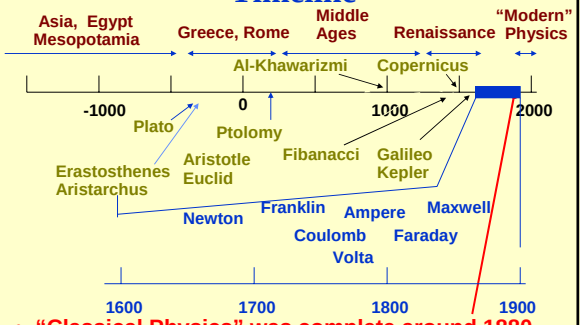
speed of light?



Maxwell

Einstein

Timeline



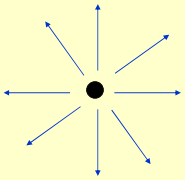
- "Classical Physics" was complete around 1880
- See Timeline description of lives of various scientists on WWW pages.

Finishing classical physics

- Electricity
  - Charges – Coulomb's law for electric forces
  - Magnetic forces
- Fields
  - Idea due to Faraday
- Maxwell put it together
  - Electromagnetism
  - Electromagnetic waves
  - Travel at speed of light!
  - Light is electromagnetic wave (radio, x-ray, ...)
- Waves
  - Interference!
  - Traveling waves
  - Standing waves
- Particles vs. Waves

The Field Concept

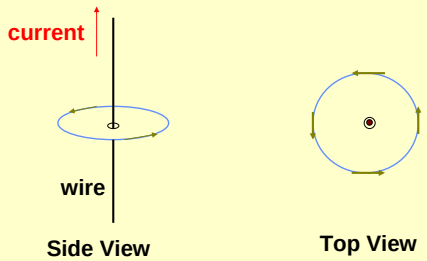
- Michael Faraday (1791 -) had the idea that forces between bodies were cause by Fields that fill all space and act on the bodies
- Electric Field E due to charge



- Faraday discovered the important connection between Electric Fields & Magnetic Fields:
  - A moving or changing electric field generates a magnetic field and a moving or changing magnetic field generates an electric field.

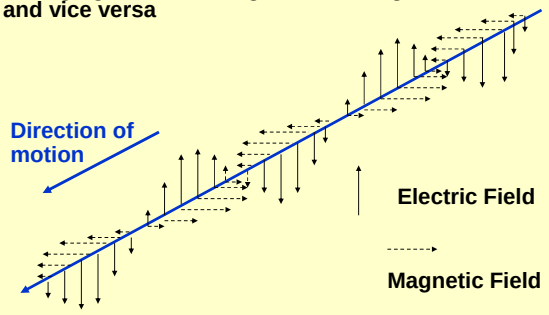
Magnetic Forces due to Electric Current

- Current is charges in motion
- Causes force on magnet
- Example: Compass near wire with current



Electromagnetic Wave

- Electromagnetic wave in vacuum (free space)
- Changing electric field generates magnetic field and vice versa



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Waves

- Important example: Periodic waves
  - Repeated identical waves:

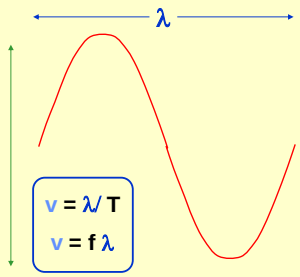
λ = wavelength = distance it takes for pattern to repeat

f = frequency = number of times a given point reaches maximum each second

f = 1/T, T = period = time between maxima

v = velocity of wave

Amplitude = max to min variation

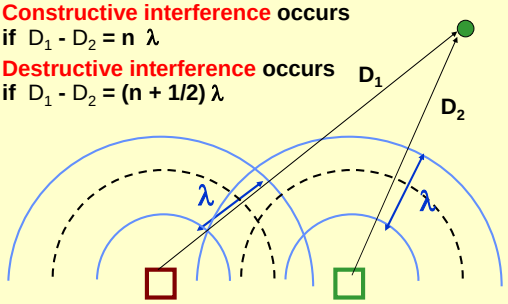


$v = \lambda / T$

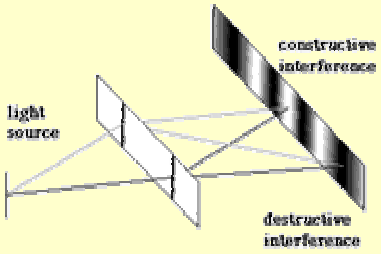
$v = f \lambda$

Conditions for Interference of Waves

- If any type of wave is emitted from two sources "in phase", i.e, the highs and lows are emitted simultaneously
- Constructive interference occurs if $D_1 - D_2 = n \lambda$
- Destructive interference occurs if $D_1 - D_2 = (n + 1/2) \lambda$

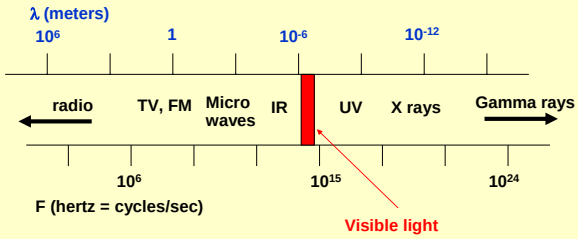


Another view of interference Light is a wave!



The range of electromagnetic waves

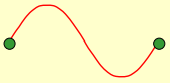
- All waves have velocity given by $v = f \lambda$
- Electromagnetic waves have velocity v = c in vacuum
- Therefore $c = f \lambda$ or $f = c / \lambda$ or $\lambda = c / f$



Standing Waves

- Waves with boundary conditions.. e.g. hold both ends of a string fixed as in a guitar.
  - velocity of any wave produced (by plucking the string) is determined by the medium.. in this case the type of the string.
  - For a fixed length of string, only waves with certain wavelengths can be standing waves... namely those wavelengths which have zeroes at the ends of the string.
  - Therefore only certain frequencies will be heard.. namely those which correspond to the definite wavelengths via $f = v / \lambda$.

$L = \lambda / 2$ fundamental: lowest frequency



$L = \lambda$ first harmonic: higher frequency

Summary of Classical Physics

- Physics as it stood near the end of the 19th Century
- Fundamental concepts:
  - Time flows the same everywhere for all observers
  - Space is described by 3 dimensions (Euclidean Geometry)
  - Mass is never created nor destroyed (conserved)
  - Charge (plus and minus) total is conserved
  - Energy changes form but is conserved
  - Momentum is conserved
- Fundamental Objects and Laws:
  - Particles have mass and move according to Newton's laws
  - Force originates in interactions between particles of matter
    - baseballs, rockets, ...
  - Waves are moving patterns in a medium - e.g. light is described by Maxwell's laws
    - Sound, Light, ...
- Waves have interference -- Particles do not

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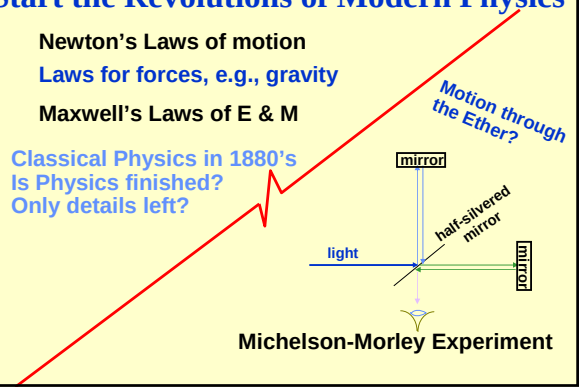
Summary of Classical Physics Start the Revolutions of Modern Physics

Newton's Laws of motion

Laws for forces, e.g., gravity

Maxwell's Laws of E & M

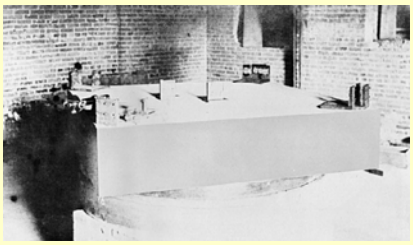
Classical Physics in 1880's
Is Physics finished?
Only details left?



Michelson-Morley Experiment

Michelson-Morley experiment

- Case School of Applied Science (Now Case Western Reserve) in Cleveland (1887)
- Speed of light the same in all directions independent of the motion of the earth!



Albert Einstein (1879-1955)

- Born German, went to university in Switzerland, became naturalized Swiss citizen.
- 1902: Job at patent office in Bern
  Does physics on the side.
- 1905: 5 Five seminal papers
  - molecular dimensions
  - Brownian motion
  - Photoelectric effect (Nobel prize)
  - Relativity
  - $E = mc^2$
- 1909: Zurich prof.
  1913: Berlin chair in Physics
  1916: General relativity

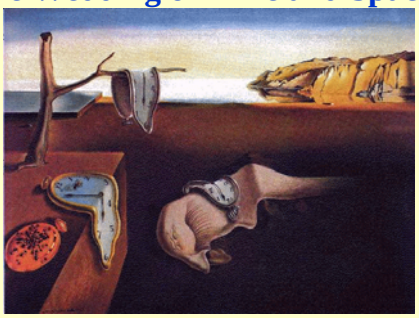
Special Relativity I

- Postulate:

  The speed of light is the same to all observers

- You can never catch light!
- Leads to change in defintion of length and time
- An object moving with respect to an observer appears to be shorter to that observer
- A clock moving with respect to an observer appears to be running slow to that observer

The Wedding of Time and Space



Moving clocks appear to run slow.
Moving objects appear to shrink along line of motion and appear distorted.
Order of events can differ for different observers.

Special Relativity

- Postulate: The speed of light is the same universal constant for all observers
- Summary in Form of Equations

$$T_{improper} = \gamma\, T_{proper}$$

$$L_{parallel}(moving) = L_{parallel}(rest) / \gamma$$

$$L_{perpendicular}(moving) = L_{perpendicular}(rest)$$

$$m(moving) = \gamma\, m(rest)$$

$$E = m c^2$$

$$\gamma = \frac{1}{\mathrm{sqrt}(1 - v^2/c^2)} > 1$$

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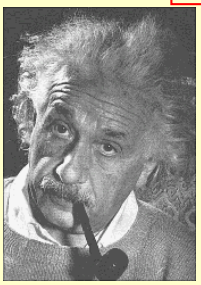
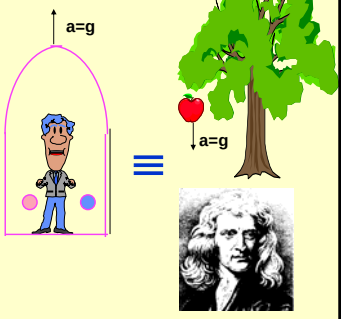
General Relativity

Equivalence Principle





Einstein's "Happiest Idea"

- **Equivalence Principle:**

  The effect of gravity is exactly the same as acceleration!

Consequence:

In an accelerating reference frame clocks run at different rates depending on position

The same applies to gravitational field

Clocks near the surface of the earth run slower than ones far from the surface

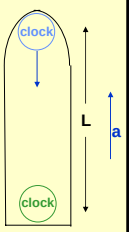
Does Gravity Also Affect Clocks?

- **We have just seen that the equivalence principle predicts that light bends in a gravitational field. What are the consequences of the equivalence principle for time?**

• The observer at the bottom observes that the clock at the top appears to run faster than his clock(at the bottom)

•**Reason: Time is defined using the speed of light.**

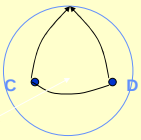
In the time it takes the pulses to travel to the bottom clock, the rocket has increased its velocity by an amount: v = at = aL/c $\beta = v/c = aL/c^2$



$f = f_0 / (1 - \beta)$

General Relativity leads to "Curved Space-time"

- **"Inertial motion" is not along "straight lines" but along the "shortest path"**
  Example of motion on surface of earth: shortest path is curved geodesic



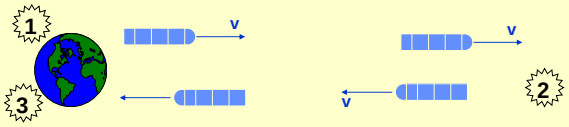
Triangle with sum of angles > 180 degrees

Newton described free fall accelerated motion as caused by "Force of Gravity"

Einstein's generality has no "force of gravity! Accelerated free fall is inertial motion in curved space-time!

Twin "Paradox" Rocket Twin is Younger!

- **The key is: The Rocket Twin accelerated while the Earth Twin didn't! The acceleration distinguishes the two twins and prevents us from applying the principle of relativity.**
- **The Calculation: Identify 3 Events:**



• **The Rocket Twin measures proper time for both time intervals: 1-2 and 2-3. Therefore the Rocket Twin measures the smallest time interval from 1-3!**

Impact of Revolution of Relativity

- **Enormous impact upon society and intellectual thought in 20th Century**
- **Dominated by Einstein's ideas**
  - **Speed of light c is a fundamental constant of nature**
  - **Postulates, "Gedanken Experiments"**
  - **Equivalence Principle**
- **Total revision of our concepts of space and time**
  - **space and time unified to form space-time**
- **Mass and Energy unified - $E = mc^2$**
  - **Enormous practical consequence**
- **Matter, Space-Time, Gravity unified**
  - **Essential to understand the universe - more later**
- **For everyday problems, Newton's laws are still completely adequate!**