The Fizeau Experiment

The Luminiferous Aether and Special Relativity

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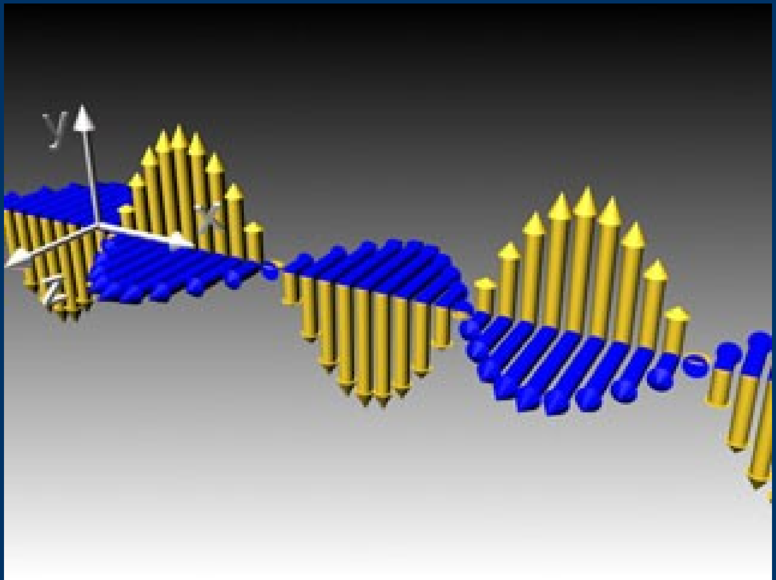


What is Light?

Modern Theories of Light

- “Plenum”
- Particle Theory
- Wave Theory
- Electromagnetic Theory
- Special Theory of Relativity
- Particle Theory... again
- Quantum Theory
- Wave-Particle Duality
- Quantum Electrodynamics

“Plenum”

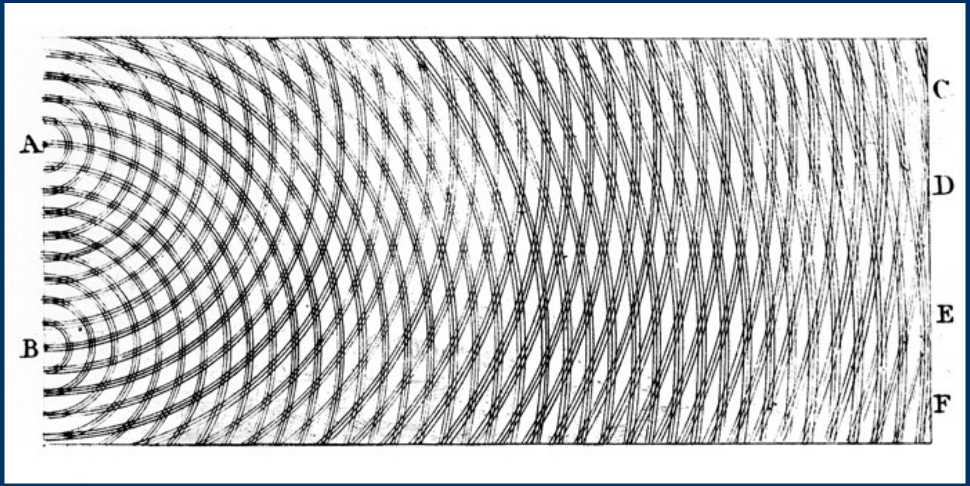
- René Descartes (1596-1650)
- Light is a disturbance of the “plenum”
- 1637 – published a theory of refraction based on the speed of light in different media
- Forerunner of the wave theory of light

Particle Theory

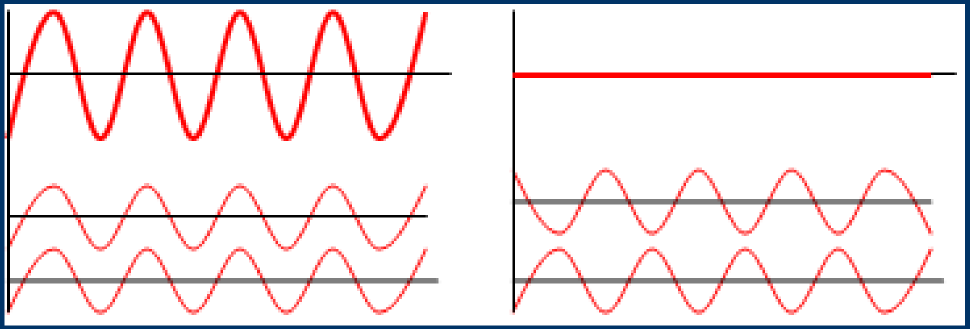
- Ibn al-Haytham (965-1040), Avicenna (980-1037)
- Pierre Gassendi (1592-1655), Isaac Newton (1643-1727)
- Newton held that light was made of particles of matter emitted omnidirectionally from a source
- Pierre-Simon Laplace (1749-1827) went further and proposed that a body could be so massive that particles of light could not escape it

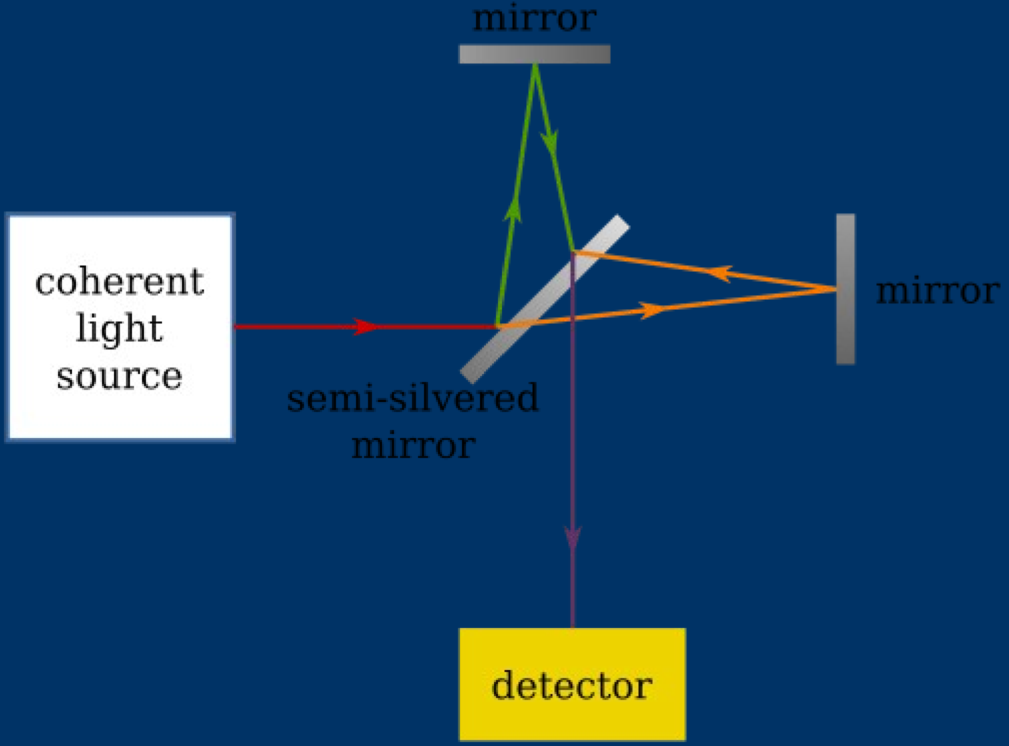
Wave Theory

- Robert Hooke (1635-1703), Christiaan Huygens (1629-1695)
- Thomas Young (1773-1829) noted that light, as a wave, could interfere with itself
- Young's double-slit experiment demonstrated light interfering with itself; consistent with the picture of light as a wave
- Luminiferous aether was proposed as a medium



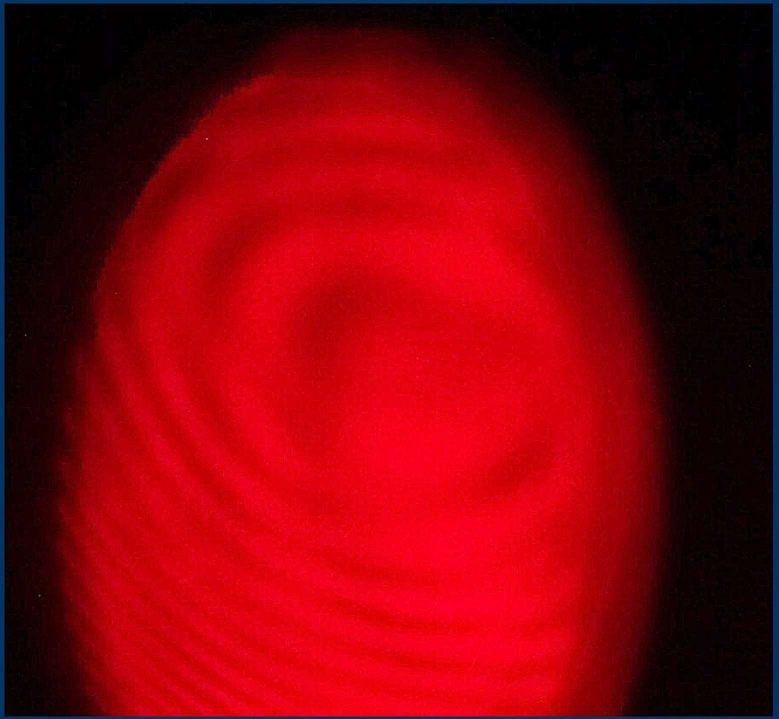
Interference





Michelson-Morley Experiment (1887)

- The aether should move with respect to the Earth
- Michelson-Morley experiment tried to detect this aether wind with an interferometer
- By changing the orientation of the interferometer to the aether wind, a fringe shift of 40% should have been seen
- A fringe shift of < 1% was observed



Arago

- 1810, François Jean Dominique Arago
- variations in refractive index of medium (as predicted by corpuscular theory) viable method for measuring the velocity of light
- Null result
  - expected different angle of refractions - different velocities of different stars at different locations and of earth at different times
  - observed only ordinary stellar abberation
  - corpuscular model arguments for the result: velocity of source influence emitted light
  - Fresnel's hypothesis formulated to explain Arago's null result

- Arago, corpuscular-ist
  - Bradley aberration not adequate to detect speed differences of starlight
  - velocity of source influence speed of emitted light
  - speed of starlight affected by gravitational field of star
- Arago's experiment
  - hypothesis – refraction of light by prism depended on prism's velocity
  - prism moves with Earth, so every starlight's deivaations would depend on direction of light with respect to Earth's motion

- Scientific progress!
  - fails to detect different in starlight speeds
  - realises method could be applied to make evident the motion of Earth
  - fails to exhibit motion of Earth
- Arago's interpretation of null result
  - while sources emit light of varying velocities, human eyes are sensitive to a narrow band of corpuscles

Fresnel

- 1818, Augustin-Jean Fresnel
- Aether is immutable and pervaded all body (making it an absolute frame in the Newtonian sense)
- Fresnel's modification – elastic aether
  - Flow of aether depended on properties of the body
  - Aether inside substance moves with respect to the (exterior) universal aether
  - Prism at rest in local aether, no differences of velocities would appear (speed of light is a property of ether)
    - Aether vibration (light) does not propagate inside Earth due to interference of secondary waves

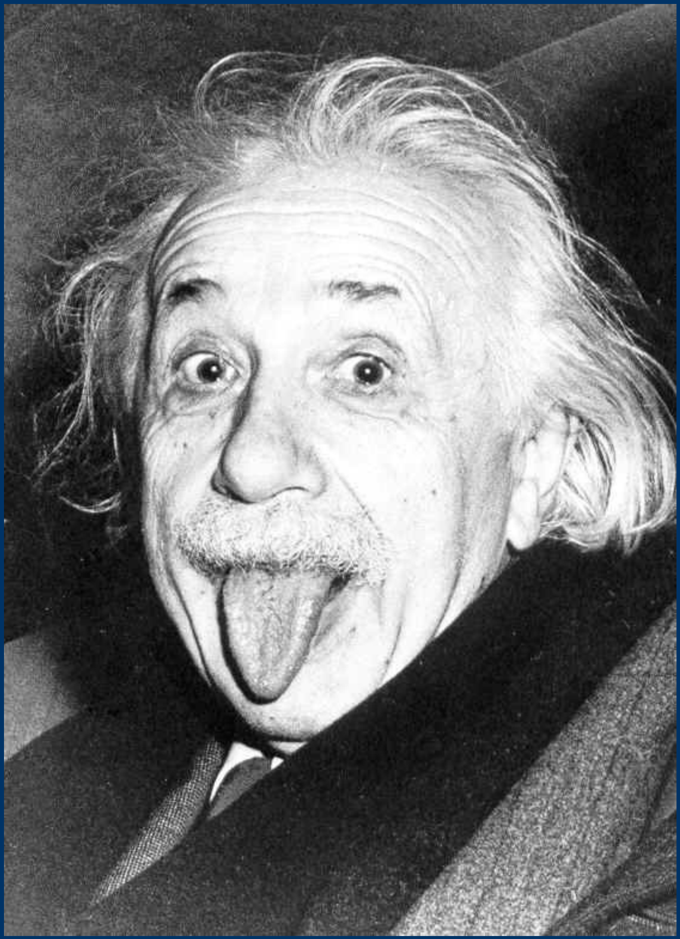
- velocity of waves in elastic material proportional to inverse square root of material density
- density of aether in water or glass greater than that in air
  - explained away by Fresnel through 'dragging of ether'
    - excess ether in prism (because of the lower speed of light)
    - excess of ether is dragged when prism moves
    - Fresnel Drag Coefficient
- problems remained (refraction indexes of material vary with frequency – which requires different aether for different velocity)

Fizeau

- 1851, Armand Hippolyte Louis Fizeau
- yellow light, two water-filled telescopes
- results upports Fresnel's hypotheses

Special Relativity

- Theory of inertial reference frames proposed by Albert Einstein in 1905 in the paper “On the Electrodynamics of Moving Bodies”
- Principle of Relativity and Invariance of the Speed of Light



Composition of Velocities in Special Relativity

- If we change from one inertial reference frame (t,x,y,z) to another inertial reference frame (t',x',y',z') moving in the x direction with velocity v, the Lorentz transformation relates the two coordinate systems:

$$t' = \gamma\left(t - vx/c^2\right)$$
$$x' = \gamma\left(x - vt\right)$$
$$y' = y$$
$$z' = z$$

$$\gamma = \frac{1}{\sqrt{1 - \left(\frac{v}{c}\right)^2}}$$

- Thus, if we have a velocity w = dx/dt in the first reference frame, then in the new reference frame it becomes

$$\frac{dx'}{dt'} = \frac{dx'}{dt}\left(\frac{dt'}{dt}\right)^{-1}$$

$$\frac{dx'}{dt'} = \left(\gamma\frac{dx}{dt} - \gamma v\right)\left(\gamma - \frac{\gamma v}{c^2}\frac{dx}{dt}\right)^{-1}$$

$$w' = \frac{w - v}{1 - wv/c^2}$$

Application of the Composition of Velocities

- Light travels at a speed of c/n through a stationary medium with refractive index n
- If the medium is flowing with speed v in the same direction as the light, then the new velocity of the light is

$$\frac{\frac{c}{n}+v}{1+\frac{\frac{c}{n}v}{c^2}}=\frac{\frac{c}{n}+v}{1+\frac{v}{c\,n}}$$

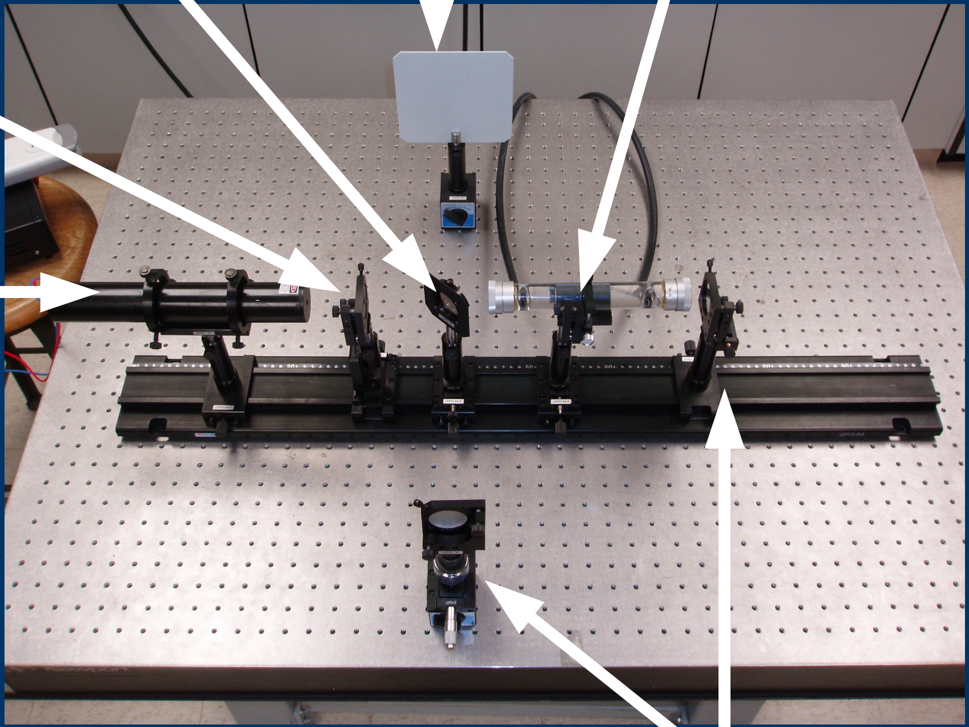
- Assuming v << c, the difference between the above equation and c/n is

$$\frac{\frac{c}{n}+v}{1+\frac{v}{cn}}-\frac{c}{n}=\frac{\frac{c}{n}+v-\frac{c}{n}\left(1+\frac{v}{cn}\right)}{1+\frac{v}{cn}}=\frac{v\left(1-\frac{1}{n^2}\right)}{1+\frac{v}{cn}}\approx v\left(1-\frac{1}{n^2}\right)$$

Equipment List

- Laser
- Beam Spreader
- Beam Splitter
- Mirrors (2)
- Water Flow Chamber
- Water Source
- Viewing Screen
- Video Camera

Experimental Setup



Procedure

- Set up equipment as in previous image, minus beam spreader and water chamber
- Align the mirrors so that the laser points on the screen “twinkle”
- Place the water chamber, taking care to not touch any of the equipment
- Insert the beam spreader
- Take observations

Measurement Method

- Analyze the position of interference pattern with still water
- Compare with the position of fringes when water is moving
- The displacement of a fringe per fringe width is the *fringe shift*
- Allows determination of optical path length difference in trials

Measurement Method (cont.)

Click to view movies
Fringe Pattern with Still Water
Fringe Pattern with Moving Water

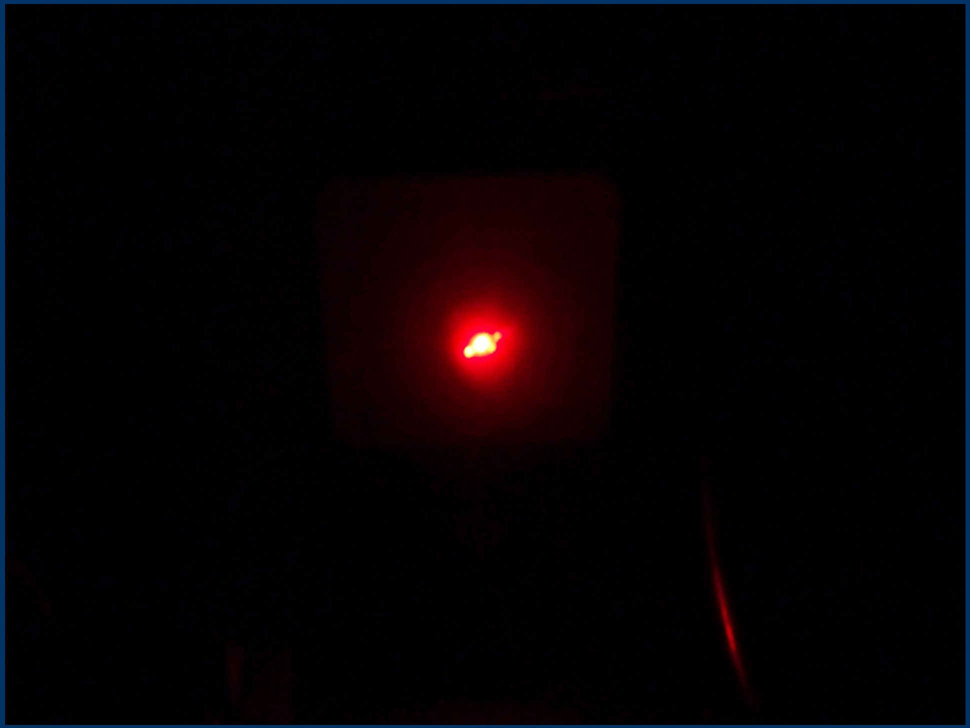
- Experimental setup is highly sensitive to vibration
- To work around this, video was taken of the interference pattern
- Video was then analyzed frame-by-frame to establish the fringe’s position
- Example frames were chosen, then compared to measure fringe shift

Experimental Obstacles

- Difficult to align
- Very sensitive once aligned
- Vibrations
  - Recall that Michelson-Morley floated their interferometer on a pool of mercury to reduce vibrations
  - We took videos and analyzed them to compensate for vibrations
- Low fringe contrast
  - Videos of fringes taken in pitch black, and barely managed to get usable data
  - Could be remedied by more sophisticated camera setup

Experimental Obstacles
Light Scattering

Without Water Chamber



With Water Chamber

Water Flow Determination

- Measured via mass per time
  - Bucket was filled with water for a timed interval
  - Water was weighed to determine mass
- Interior diameter of water tube, since it is not able to be opened, was estimated by measuring the outside diameter and estimating the thickness of the glass
- Water flow was calculated using the volume of water per time, divided by the cross sectional area

Results

Measured Water Speed

Trial 1: 0.0325 +/- 0.0080 m/s
Trial 2: 0.0816 +/- 0.0097 m/s
Trial 3: 0.0495 +/- 0.0044 m/s

Expected Fringe Shift $\frac{4 L n^2 v}{\lambda c}\left(1-\frac{1}{n^2}\right)$	Measured Fringe Shift
Trial 1: 0.0150%	25%
Trial 2: 0.0377%	40%
Trial 3: 0.0229%	30%

Measured Velocity of Light in Moving Water $\frac{c}{n}+v\left(1-\frac{1}{n^2}\right)$

Trial 1: 2.25×10^8 m/s
Trial 2: 2.25×10^8 m/s
Trial 3: 2.25×10^8 m/s

Further Understanding of Light

- Electromagnetic Theory
- Particle Theory… again
- Quantum Theory
- Wave-Particle Duality
- Quantum Electrodynamics