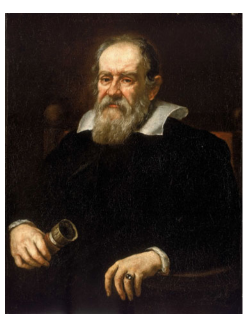
Light

How Fast is Light?

Historical Measurements of the Speed of Light

- Galileo Galilei (Italian, 1564 – 1642)
  - Two people with lanterns very far apart
  - Light must travel at least ten times faster than sound

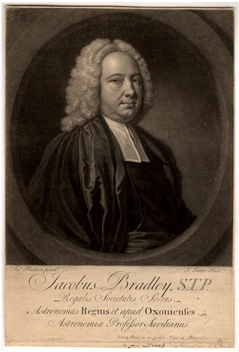


Justus Sustermans (public domain)

- Ole Rømer (Dutch, 1644 – 1710)
  - Compared the duration of Io’s orbits as Earth moved towards and away from Jupiter
  - Light takes around 22 minutes to reach earth

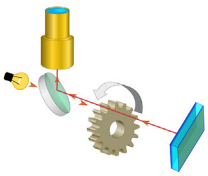
Jacob Coning (public domain)

- James Bradley (English, 1692 – 1762)
  - Angular variation in light hitting earth
  - 297,729 km/s



James Bradley by and published by John Faber Jr, after Thomas Hudson
mezzotint, 1742-1756

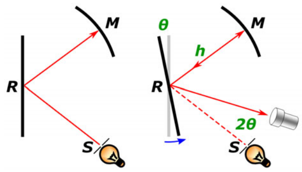
- Hippolyte Fizeau (French, 1819 – 1896)
  - Light shining through a toothed wheel



Д.Ильин (public domain)

  - 315,000 km/s

- Léon Foucault (French, 1819 – 1868)
  - Light shining on a rotating mirror

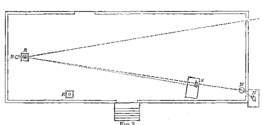


Stigmatella aurantiaca (Creative Commons Attribution-Share Alike 4.0 International license)

  - 298,000 km/s

Bertall & Cie. Source gallica.bnf.fr / BnF. btv1b8449954m (public domain {{PD-Canada}})

- Albert Michelson (American, 1852 – 1931)
  - Improved Foucault's method

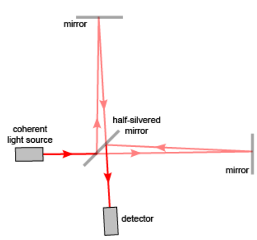


Michelson, A. Experimental Determination of the Velocity of Light. Made at the U.S. Naval Academy, Annapolis. 1880. Public Domain {{PD-Canada}}

  - 298,299.96 km/s

Source: Smithsonian Institution #SIL14-M004-01 (Public Domain {{PD-Canada}})

- National Institute of Standards and Technology (NBS) in Boulder, Colorado (1973)
  - Interferometric method with a laser
  - 299,792.4574 ± 0.001 km/s



Stannered (Creative Commons Attribution-Share Alike 3.0 Unported license)

What is Light?

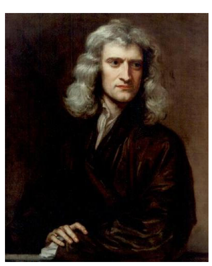
The Making of a Model

Corpuscular Model

- Rene Descartes (French, 1596-1650)
  - "Le monde de Mr. Descartes : ou, le traite' de la lumiere, et des autres principaux objects des sens : avec un discours du mouvement local, & un autre des fiévres / composez selon des principes du même auteur." (1664)

Frans Hals – Public Domain

- Isaac Newton (English, 1642 – 1726)
  - "Opticks: or, a Treatise of the Reflections, Refractions, Inflections and Colours of Light." (1730)



Godfrey Kneller (public domain)

- Light is made up of corpuscles (small discrete particles) which travel in a straight line with a finite velocity and possess energy.
- Every source of light emits large numbers corpuscles in a medium surrounding the source.
- These corpuscles are perfectly elastic, rigid, and weightless.
- The size of the corpuscle indicates the color.

Wave Model

- Christiaan Huygens (Dutch, 1629 – 1695)
  - "Traite de la lumiere. Où sont expliquées les causes de ce qui luy arrive dans la reflexion, & dans la refraction. Et particulierment dans l'etrange refraction du cristal d'Islande, par C.H.D.Z. Avec un Discours de la cause de la pesanteur." (1690)

Caspar Netscher (public domain)

Which Model is Better?

- Both models were able to describe the behaviors of light.
- The corpuscular model of light was adopted mostly due to Newton's stature within the scientific community.
- Further experimentation would change that idea.

- Thomas Young (British, 1773 – 1829)
  - "Experiments and Calculations Relative to Physical Optics" (1804)
  - Demonstrated that light will diffract and cause areas of constructive and destructive interference
    - Something only waves can do.

Henry Briggs (public domain)

- Augustin-Jean Fresnel (French, 1788 – 1827)
  - Le Mémoire de Fresnel sur la diffraction de la lumière (1816)
  - Expressed Huygens's principle of secondary waves and Young's principle of interference in quantitative terms
  - Proposed that simple colors consist of sinusoidal waves

Unknown (public domain)

- Fresnel gave the first satisfactory explanation of diffraction by straight edges, including the first satisfactory wave-based explanation of rectilinear propagation.
- By further supposing that light waves are purely transverse, Fresnel explained the nature of polarization, the mechanism of chromatic polarization, and the transmission and reflection coefficients at the interface between two transparent isotropic media.

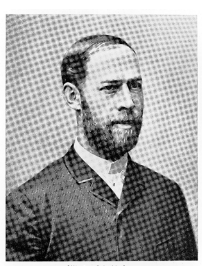
- Léon Foucault (French, 1819 – 1868)
  - "Sur les vitesses relatives de la lumière dans l'air et dans l'eau." (1853)
  - Showed that the speed of light in water was slower than in air

Bertall & Cie. Source gallica.bnf.fr / BnF. btv1b8449954m (public domain {{PD-Canada}})

- Foucault's measurement of the speed of light was the final definitive proof that the wave model was more correct than the corpuscular model.

Photoelectric Effect

- Heinrich Hertz (German, 1857 – 1894)
  - "Ueber einen Einfluss des ultravioletten Lichtes auf die electrische Entladun. Annalen der Physik." Volume 267, Issue 8. 1887
  - When ultraviolet light shines on two metal electrodes with a voltage applied across them, the light changes the voltage at which sparking takes place



H. Hertz, 19thC, from Lenard, Grosse Naturforscher, 1930. Wellcome Collection.

- Philipp Lenard (Hungarian, 1862 – 1947)
  - “Ueber die lichtelektrische Wirkung.” Annalen der Physik. Volume 313. Issue 5. 1902
  - The maximum velocity with which electrons leave a metal plate after it has bee illuminated with ultraviolet light is independent of the intensity of the light.

Unknown (public domain)

Problem

- According to the wave model of light, this should not happen.
  - The energy of a wave is related to its intensity.

- Albert Einstein (German, 1879 – 1955)
  - “Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt.” Annalen der Physik. Volume 322. Issue 6. 1905.
  - Proposed that light is made of energy quanta

Lucien Chavan (public domain)

- “Energy, during the propagation of a ray of light, is not continuously distributed over steadily increasing spaces, but it consists of a finite number of energy quanta localised at points in space, moving without dividing and capable of being absorbed or generated only as entities.”

A. Einstein (translated – Dirk ter Haar)

- The amount of energy that a photon has is fixed and depends on its wavelength (and thus frequency)
- Photons with enough energy knock the electrons out of the metal
  - If the photon does not have enough energy, nothing happens

Quantum Theory of Light

- Light (and matter) is composed of small particles that have wave-like properties
  - It is really both a particle and a wave at the same time
  - It exhibits particle or wave behavior depending on the situation

Wave-Particle Duality

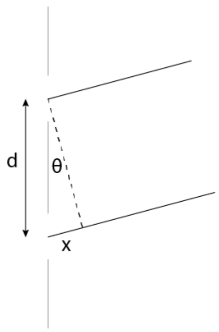
- Light has properties of both particles and waves.
- Quantum theory tells us that both light and matter consist of tiny particles which have wavelike properties associated with them.
  - light is composed of particles called photons
  - matter is composed of particles called electrons, protons, neutrons

Young's Experiment in Detail

Mathematical Calculations

I made a small hole in a window-shutter, and covered it with a piece of thick paper, which I perforated with a fine needle. For greater convenience of observation I placed a small looking-glass without the window-shutter, in such a position as to reflect the sun's light in a direction nearly horizontal upon the opposite wall, and to cause the cone of diverging light to pass over a table on which were several little screens of card-paper. I brought into the sunbeam a slip of card about one-thirtieth of an inch in breadth, and observed its shadow, either on the wall or on other cards held at different distances. Besides the fringes of color on each side of the shadow, the shadow itself was divided by similar parallel fringes of smaller dimensions, differing in number according to the distance at which the shadow was observed, but leaving the middle of the shadow always white.

Thomas Young. Experiments and Calculations Relative to Physical Optics. A Bakerian Lecture. Read November 24, 1803. Philosophical Transactions. 1804.



d – distance between slits

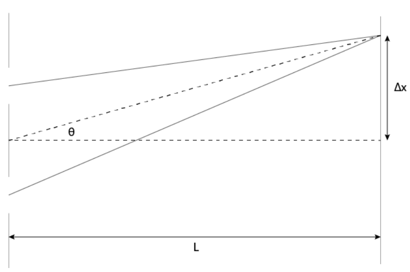
x – path length difference

$$\sin\theta = \frac{x}{d}$$

For constructive interference, x must be equal to λ.

$$\sin\theta = \frac{\lambda}{d}$$

- The interference pattern appears on a screen a distance L away.



Δx – the distance between the areas of constructive interference (bright spots)

$$\tan\theta = \frac{\Delta x}{L}$$

- If $L >> \Delta x$, then θ is a small angle
- For small angles (measured in radians)

$$\sin\theta = \tan\theta$$

- Therefore

$$\frac{\lambda}{d} = \frac{\Delta x}{L}$$

$$\boxed{\lambda = \frac{\Delta x d}{L}}$$

Example

- Red light of wavelength 680 nm is incident on a double slit separated by 50 µm. How far apart are the bright fringes on a screen 1.5 m away?

$$\lambda = \frac{\Delta x d}{L}$$

$$\Delta x = \frac{L\lambda}{d} = \frac{(1.5\text{ m})(680 \times 10^{-9}\text{ m})}{50 \times 10^{-6}\text{ m}} = 0.02\ m$$