The Nature of Light

The Classical View of Light: Light as Particles

Properties and Characteristics of Visible Light

Apparent Brightness or Intensity
Perceived Color
Energy Content (ability to heat)
Straight Line Propagation (shadows, etc.)

The Classical Interpretation

Empedocles (c. 490 - 430 BCE) - Ptolemy (c. 90 - 168)
The Classical Elements: Earth, Water, Air, and Fire
(Light was a separate fundamental element in some ancient schools)

Empedocles: Light as "Fire from the eyes"
Euclid (c. 300 BCE): Counter argument: "In a blink of the eye"
Lucretius (55 BCE) The corpuscular nature of light - photons

Questions

Is color intrinsic or a manifestation of photon speed?
Is the speed of light finite or infinite?

The Behavior of Light: Classical Optics

Euclid (c. 300 BCE) ***Optica***

• **Light travels in straight lines (in a uniform medium)**

This accounts for the inverse square law for light

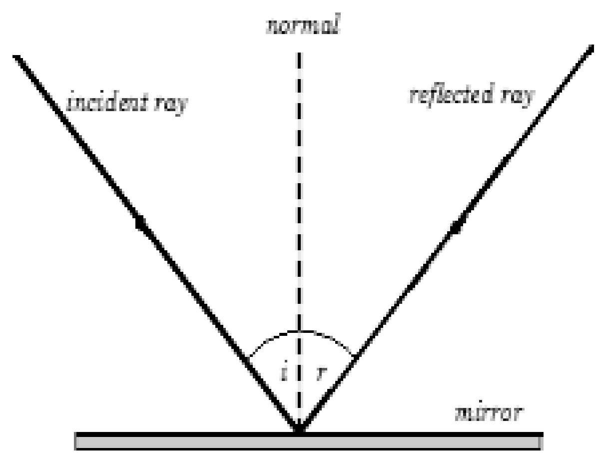
$$F = L/4\pi d^2$$

Johannes Kepler *The Optical Part of Astronomy* (1604)

• **The Law of Reflection**

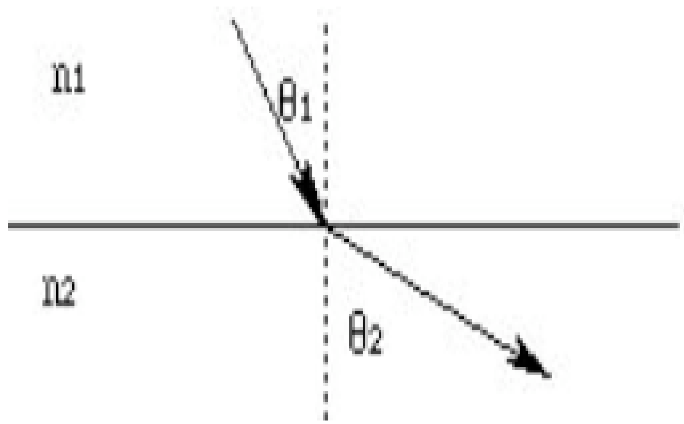
The angle of reflection equals the angle of incidence

i = r



Classical Optics
(continued)

• **The Law of Refraction**
Ptolemy (c. 150 CE) ***Optics***



Snell's Law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$
Willebrord Snellius (1580 - 1626)

Digression: The index of refraction, n
$n_{medium} = c_{vacuum}/c_{medium} \geq 1$
$n_{vacuum} = 1$
also: $n_{medium} = n(\lambda)$
Associated Phenomena: Dispersion, Total Reflection

The Nature of Light: Light as a Wave

Francesco Grimaldi observes <u>diffraction</u> (1665)

René Descarte's *plenum* (1637)

(Analogy with sound: Denser means faster, refraction)

Christian Huygen's *luminiferous æther* (1690)

(Denser means slower, refraction)

But:

Newton's Corpuscular Theory (*Opticks* 1704)

(Refraction and diffraction explained by a "gravitational" effect)

<u>The Properties of the Luminiferous Æther</u>

If light is a wave it must be carried by some medium with suitable properties:

- **elasticity or viscosity**
- **mass?**
- **permeability**
- **Light speed is relative to the medium**
- **Light speed in the medium independent of wavelength)**

The Nature of Light

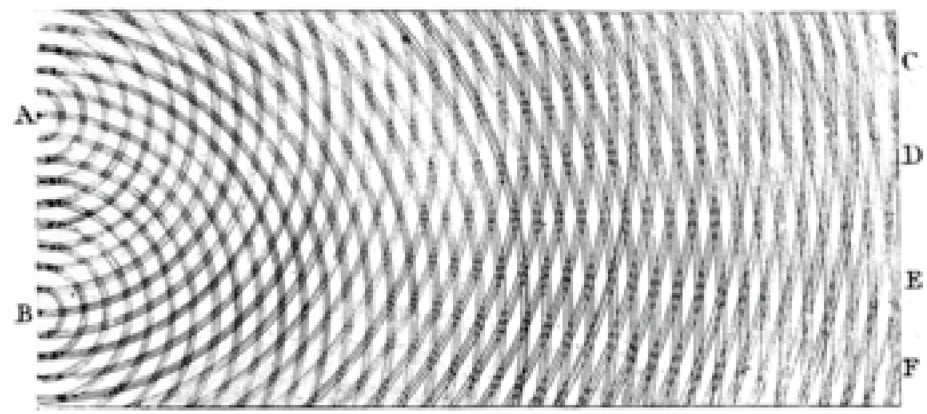
Light is a Wave!

Thomas Young (1773 - 1829) The Double Slit Experiment

- Diffraction
- Interference

also

- Polarization: Light is a Transverse Wave
(... and hence the æther is not a "fluid"!)



Drawing showing diffraction & interference (Thomas Young 1803)

- Note <u>periodic</u> sequence of intensity maxima on the right.
- Spacing of "interference fringes" is proportional to the wavelength.

The Speed of Light

Question: Is The Speed of Light Finite or Infinite?
Empedocles (490 - 430 BCE) *versus* Euclid (c. 325 - 365 BCE)
and
Descartes (1596 - 1650) *versus* Galileo (1564 - 1642)

Measuring the Speed of Light

- **Ole Rømer (1676): The orbital motion of Io (1676)**
  $c = 227{,}000$ km s^{-1} (2 au in 18 minutes)

- **James Bradley: The aberration of starlight (1728)**

- **Hippolyte Fizeau (1849) and Léon Foucault (1862)**
  Cogwheels and spinning mirrors: 313,000 to 298,000 km s^{-1}

- **Albert Michelson (1879 & 1926)**
  (Mt. Wilson to Mt. San Antonio, California)
  $c = 299{,}796$ km s^{-1}

Today: **c = 299,792,458** m s^{-1} (exactly!)

(1 second = 9,192,631,770 periods of ^{133}Cs hyperfine $^{2}S_{1/2}$ ground state transition)

Light as an Electromagnetic Wave

Maxwell's Equations

James Clerk Maxwell (1831-1879)

$\nabla \times \mathbf{H} = \mathbf{J} + \partial \mathbf{D}/\partial t$	Ampère's law (extended)
$\nabla \times \mathbf{E} = -\partial \mathbf{B}/\partial t$	Faraday's law
$\nabla \cdot \mathbf{D} = \rho$	Coulomb's law (Gauss's Law)
$\nabla \cdot \mathbf{B} = 0$	(Maxwell; Magnetic dipolarity!)

E and **D**, and **H** and **B** describe the electric and magnetic fields;
ρ and **J** represent the charges and currents responsible for those fields

Constitutive Relations

$\mathbf{D} = \varepsilon \mathbf{E}$..........permittivity
$\mathbf{B} = \mu \mathbf{H}$.........permeabiliy
$\mathbf{J} = \sigma \mathbf{E}$......... "Ohm's Law"
$\nabla \cdot \mathbf{J} = -\partial \rho/\partial t$.....Charge Conservation

The quantities ε,μ,σ,and ρ, are (measurable) properties of the medium

Electromagnetic Waves

Wave Equation

$$\nabla^2 \mathbf{E} - (\mu\varepsilon)\, \partial^2 \mathbf{E}/\partial t^2 = 0 \qquad (\text{if } \sigma = 0)$$

This represents a wave propagating with speed $v = (\mu\varepsilon)^{-1/2}$

In a vacuum: $v_{vacuum} = (\mu_o \varepsilon_o)^{-1/2} =$ 310,740,000 m s^{-1} Maxwell (1865)

Electromagnetic Waves and Electromagnetic Forces

Electric and magnetic fields can exert forces on charged masses

$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$ The Lorentz Force

An electromagnetic wave carries both energy and momentum - but no mass!

$\mathbf{S} = \mathbf{E} \times \mathbf{H}$ Energy Flux (Poynting's Vector)

and $\mathbf{P} = \mathbf{S}/c$ Momentum Flux (or Pressure)

Maxwell's Electromagnetism

Maxwell (1865):

- Electric and magnetic forces propagate at the speed of light.
- Electromagnetic waves propagate at the speed of light.
- Electromagnetic Waves carry energy and momentum.
- Electromagnetic waves have transverse polarization.
- Light appears to have all of the properties of such a wave

therefore

- Light is almost certainly an electromagnetic wave
- Other kinds of electromagnetic waves should exist

(Let's build a radio!)

- The electromagnetic æther and the luminiferous æther are the same.

But there seemed to be a problem:

"Maxwell's Equations are not invariant under the Galilean Transformation."

hence

"The Principle of Relativity is not honored."

.........say what?