Light - Geometric Optics

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Physics 202
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Chapter 35

- Nature of light
- Reflection
- Refraction
- Dispersion
- Total internal reflection

lecture notes and demonstrations

- Demonstrations:
  - Speed of light through optical fiber
  - Dispersion: Rainbow colors by prism
- Whiteboard:
  - Details on Roemer method (speed of light with Jupiter moon Io)
  - Other

Nature of light: particles?

- Until the end of the 19th century, light was considered to be a stream of particles.
- The particles were either emitted by the object being viewed or emanated from the eyes of the viewer
- Isaac Newton (1642-1727) was the chief architect of the particle theory of light
  - He believed the particles left the object and stimulated the sense of sight upon entering the eyes

  - This was the view at the end of the 18th century

Nature of light: waves?

- Christian Huygens (1629-1695) argued that light might be some sort of a wave motion
- Thomas Young (1801) provided the first clear demonstration of the wave nature of light
  - He showed that light rays interfere with each other
  - Such behavior could not be explained by particles
- During the nineteenth century, other developments led to the general acceptance of the wave theory of light
- Maxwell asserted that light was a form of high-frequency electromagnetic wave
- Hertz confirmed Maxwell's predictions

  - This was the view at the end of 19th century!

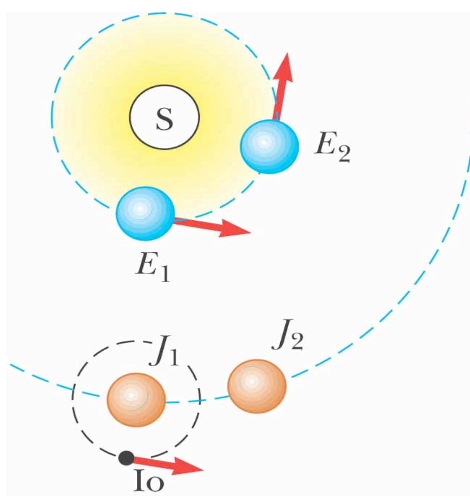
But: new problems arose just as everything seemed fine!

Nature of light: particle or wave? - or both?

- Some experiments could not be explained by the wave nature of light
- The photoelectric effect was a major phenomenon not explained by waves
  - When light strikes a metal surface, electrons are sometimes ejected from the surface
  - The kinetic energy of the ejected electron is independent of the frequency of the light

Measurement of the Speed of Light – Roemer's Method

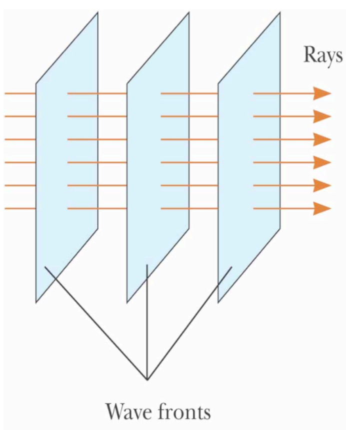
- Ole Roemer (1675) measured the periods of revolution of Io, a moon of Jupiter, as Jupiter revolved around the sun
- The periods of revolution
  - were longer when the Earth was receding from Jupiter
  - and shorter when the Earth was approaching
- Using Roemer's data, Huygens estimated the lower limit of the speed of light to be 2.3×10^8 m/s
  - Finite speed!
  - Reasonably close!



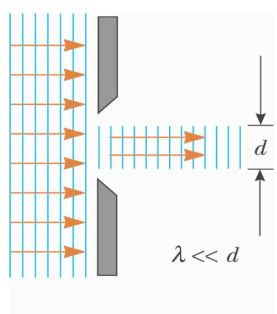
Measurement of the Speed of Light

- Demonstration:
- Measure time delay of an optical pulse through an optical fiber of 30 m length.
- Observed delay: ~ 100 nsec
- Approximately the speed of light.
- C = 30 m / 100 nsec = ……

Ray Approximation

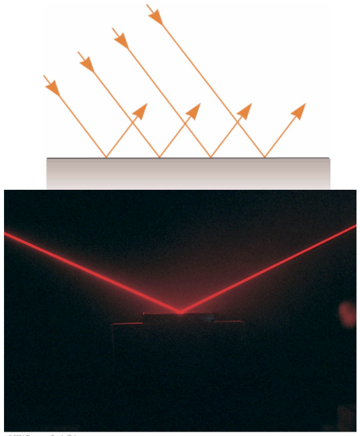


- The rays are straight lines perpendicular to the wave fronts



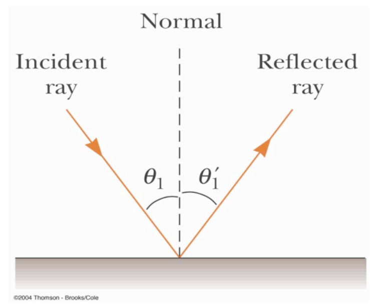
- If a wave meets a barrier, we will assume that $\lambda << d$
  - d is the diameter of the opening
- This approximation is good for the study of mirrors, lenses, prisms, etc.

Specular Reflection



- *Specular reflection* is reflection from a smooth surface

Law of Reflection



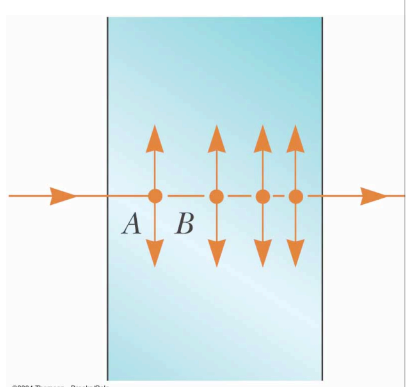
Law of Reflection

$\theta_1' = \theta_1$

The incident ray, the reflected ray and the normal are all in the same plane

Light in a Medium

- The light enters from the left
- The light may encounter an electron
- The electron may absorb the light, oscillate, and reradiate the light
- The absorption and radiation cause the average speed of the light moving through the material to decrease



The Index of Refraction

- The speed of light in any material is less than its speed in vacuum
- The **index of refraction**, *n*, of a medium can be defined as

$$n \equiv \frac{\text{speed of light in a vacuum}}{\text{speed of light in a medium}} = \frac{c}{v}$$

- For a vacuum, $n = 1$
- For other media, $n > 1$
- For air: $n=1.00029 \approx 1$

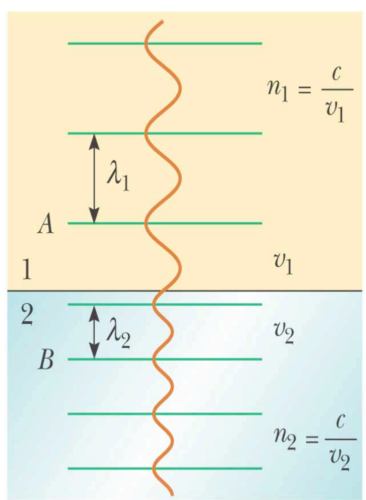
Indices of Refraction[a]

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

Frequency Between Media

- As light travels from one medium to another, *its frequency does not change*
  - Both the wave speed and the wavelength do change
  - The wavefronts do not pile up, nor are created or destroyed at the boundary, so f must stay the same
- $v = f\lambda$ *on both sides*

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$



Index of Refraction - Snell's Law

- The frequency stays the same as the wave travels from one medium to the other
- $v = f\lambda$
  - $f_1 = f_2$ but $v_1 \neq v_2$ so $\lambda_1 \neq \lambda_2$
- The ratio of the indices of refraction:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

$$\lambda_1 n_1 = \lambda_2 n_2$$

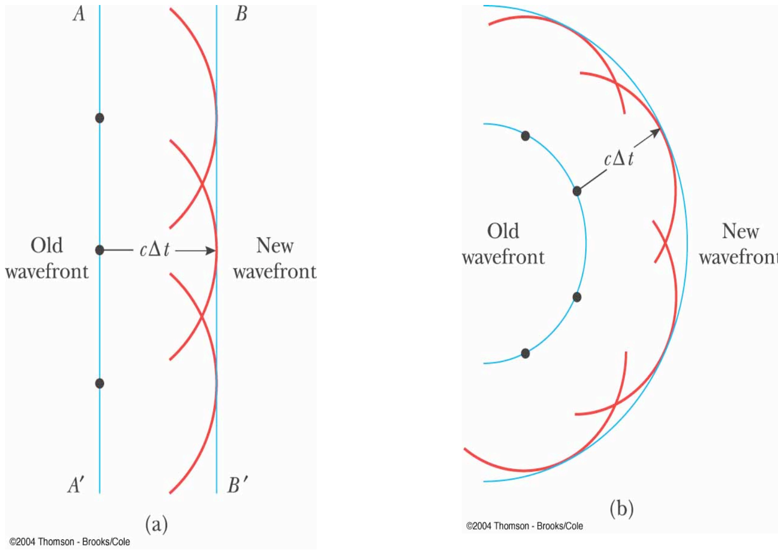
Snell's law of refraction:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Huygens's Principle

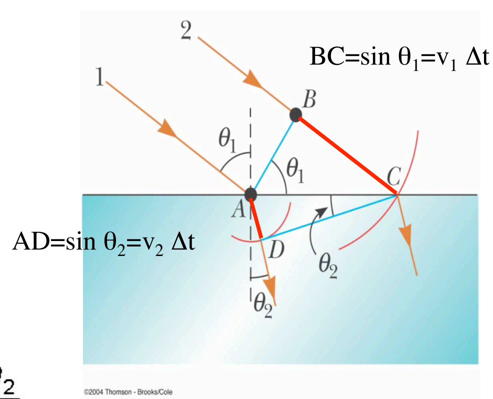
- Huygens assumed that light is a form of wave motion rather than a stream of particles
- Huygens's Principle is a geometric construction for determining the position of a new wave at some point based on the knowledge of the wave front that preceded it

Huygens's Construction for a Plane Wave



Huygens's Principle and the Law of Refraction

- Ray 1 strikes the surface and at a time interval Δt later, ray 2 strikes the surface
- During this time interval, the wave at *A* sends out a wavelet, centered at *A*, toward *D*



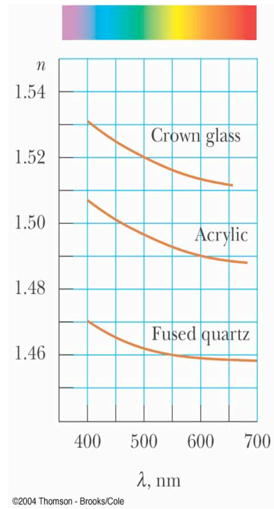
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

But $\frac{\sin\theta_1}{\sin\theta_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$

and so $n_1 \sin\theta_1 = n_2 \sin\theta_2$ Snell's Law

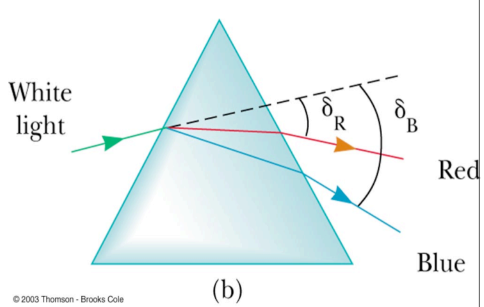
Variation of Index of Refraction with Wavelength = Dispersion

- The index of refraction for a material generally decreases with increasing wavelength
- Violet light bends more than red light when passing into a refracting material



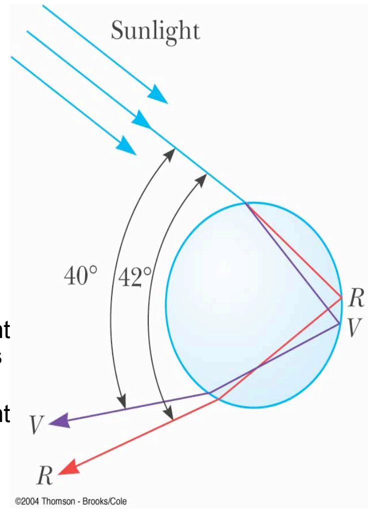
Refraction in a Prism

- Since all the colors have different angles of deviation, white light will spread out into a *spectrum*
  - Violet deviates the most
  - Red deviates the least
  - The remaining colors are in between

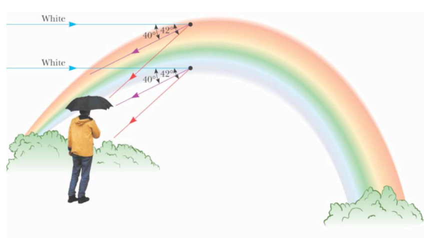


The Rainbow

- At the back surface the light is reflected
- It is refracted again as it returns to the front surface and moves into the air
- The rays leave the drop at various angles
  - The angle between the white light and the most intense violet ray is 40°
  - The angle between the white light and the most intense red ray is 42°



Observing the Rainbow



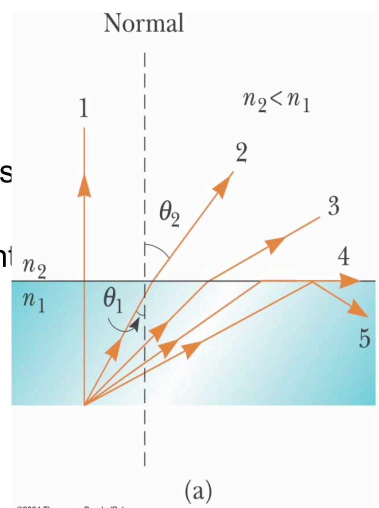
- If a raindrop high in the sky is observed, the red ray is seen
- A drop lower in the sky would direct violet light to the observer
- The other colors of the spectra lie in between the red and the violet

Total Internal Reflection

- A phenomenon called **total internal reflection** can occur when light is directed from a medium having a given index of refraction toward one having a *lower* index of refraction

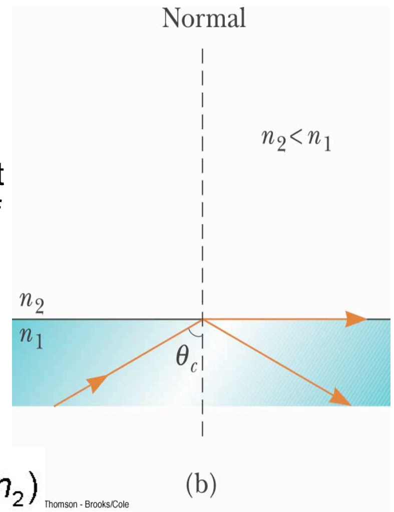
Possible Beam Directions

- Possible directions of the beam are indicated by rays numbered 1 through 5
- The refracted rays are bent away from the normal since $n_1 > n_2$



Critical Angle

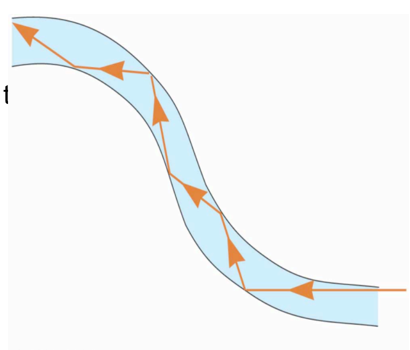
- There is a particular angle of incidence that will result in an angle of refraction of 90°
  - This angle of incidence is called the *critical angle,* θ_C



$$\sin\theta_C = \frac{n_2}{n_1} \quad (\text{for } n_1 > n_2)$$

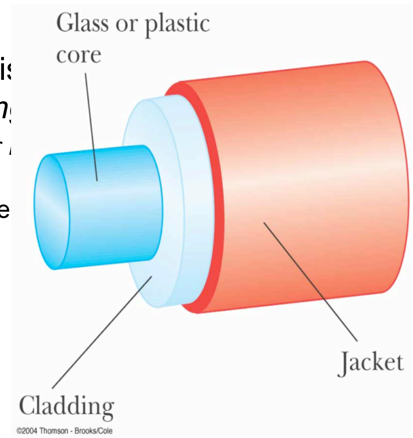
Fiber Optics

- An application of internal reflection
- Plastic or glass rods are used t "pipe" light from one place to another
- Applications include:
  - medical use of fiber optic cables for diagnosis and correction of medical problems
  - Telecommunications



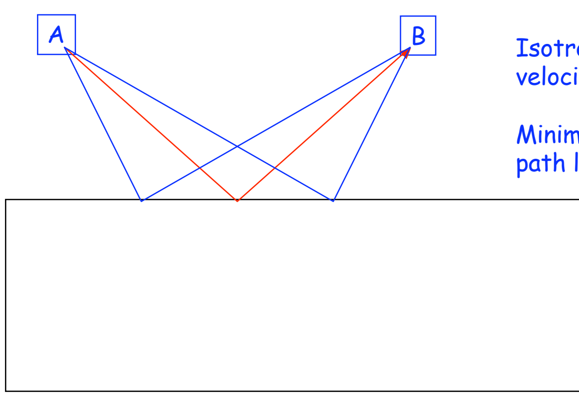
Construction of an Optical Fiber

- The transparent core is surrounded by *cladding*
  - The cladding has a lower *n* than the core
  - This allows the light in the core to experience total internal reflection
- The combination is surrounded by the jacket



Fermat's principle

The path a beam of light takes between two points is the one which is traversed in the least time.



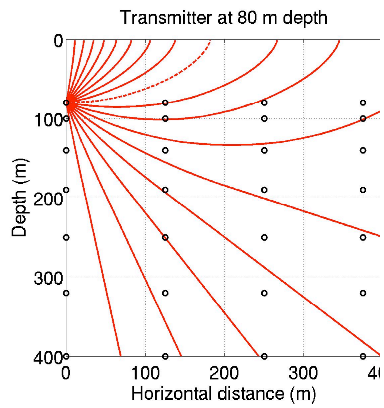
Isotropic medium: constant velocity.

Minimum time: minimum path length.

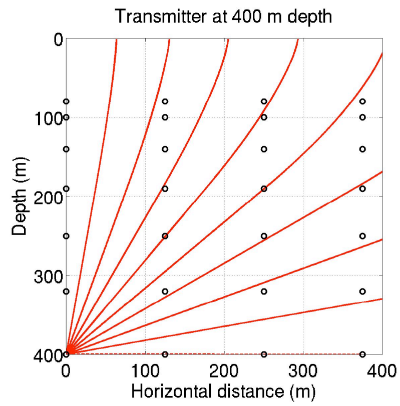
How does the light know which is the fastest way?

Example: Propagation of sound waves in ice at the South Pole

Measurable refraction in firn:



Little refraction below firn:



Understand refraction in order to understand

Fermat's principle

- Fermat's principle offers a fascinating view.
- How do the photons know which is the fastest way?
- It reminds of other principles in Physics:
  - Principle of least action.

Pool light

- A small underwater pool light is 1.00 m below the surface. The light emerging from the water forms a circle on the water surface. What is the diameter of this circle?