Part II: Light and Optics

Chapter 35

The Nature of Light and the Principles of Ray Optics

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LECTURE OUTLINE

- **35.1** The Nature of Light
- **35.2** Measurements of the Speed of Light
- **35.3** The Ray Approximation in Ray Optics
- **35.4** Analysis Model: Wave Under Reflection
- **35.5** Analysis Model: Wave Under Refraction
- **35.8** Total Internal Reflection

Introduction to Light

- Light is basic to almost all life on Earth.
- Light is a form of electromagnetic radiation.
- Light represents energy transfer from the source to the observer.
- Many phenomena depend on the properties of light.
  - Seeing a TV or computer monitor
  - Blue sky, colors at sunset and sunrise
  - Images in mirrors
  - Eyeglasses and contacts
  - Rainbows
  - Many others

Light and Optics

- There are two historical models for the nature of light.
- The speed of light has been measured in many ways.
- Reflection and refraction are the fundamental phenomena in ray (geometric) optics.
- Internal reflection is the basis for fiber optics.

The Nature of Light

- Before the beginning of the nineteenth 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.
- Newton 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.

Section 35.1

Nature of Light – Alternative View

- Christian Huygens argued that light might be some sort of a wave motion.
- Thomas Young (in 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.

Christian Huygens

- 1629 – 1695
- Best known for contributions to fields of optics and dynamics
- He thought light was a type of vibratory motion.
- It spread out and produced the sensation of light when it hit the eye.
- He deduced the laws of reflection and refraction.
- He explained double refraction.

Section 35.1

Confirmation of Wave Nature

- During the nineteenth century, other developments led to the general acceptance of the wave theory of light.
- Thomas Young provided evidence that light rays interfere with one another according to the principle of superposition.
  - This behavior could not be explained by a particle theory.
- Maxwell asserted that light was a form of high-frequency electromagnetic wave.
- Hertz confirmed Maxwell's predictions.

Section 35.1

Particle Nature

- Some experiments could not be explained by the wave model 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.
- Einstein (in 1905) proposed an explanation of the photoelectric effect that used the idea of quantization.
  - The quantization model assumes that the energy of a light wave is present in particles called photons.
  - $E = hƒ$
    - h is Planck's Constant and = 6.63×10^{-34} J·s

Section 35.1

Dual Nature of Light

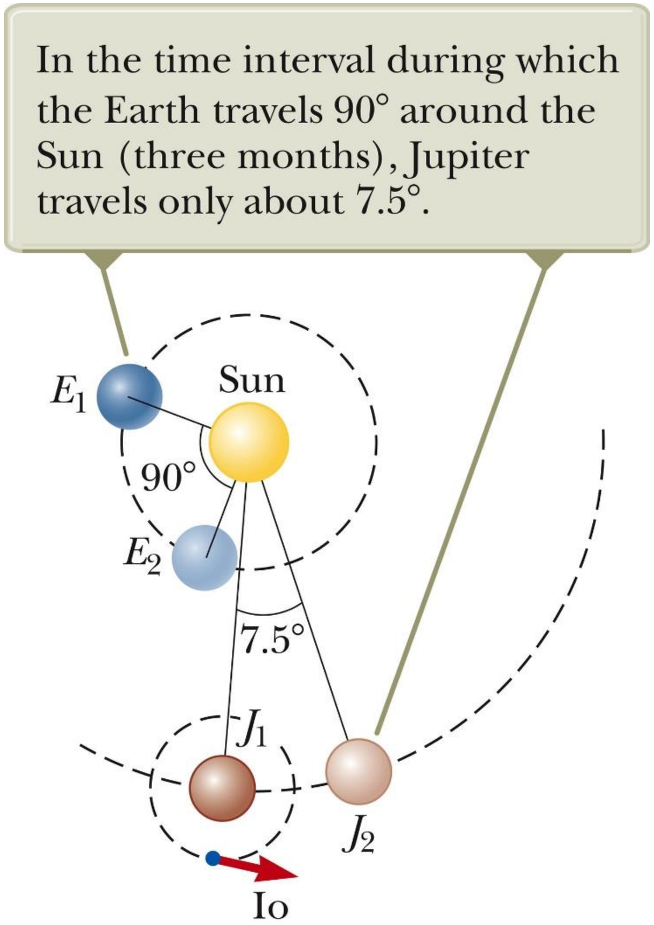
- In view of these developments, light must be regarded as having a dual nature.
- Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations.
- This chapter investigates the wave nature of light.

Measurements of the Speed of Light

- Since light travels at a very high speed, early attempts to measure its speed were unsuccessful.
  - Remember $c = 3.00 \times 10^8$ m/s
- Galileo tried by using two observers separated by about 10 km.
  - The reaction time of the observers was more than the transit time of the light.

Measurement of the Speed of Light – Roemer's Method

- In 1675 Ole Roemer used astronomical observations to estimate the speed of light.
- He used the period of revolution of Io, a moon of Jupiter, as Jupiter revolved around the sun.
- The angle through which Jupiter moves during a 90° movement of the Earth was calculated.



Roemer’s Method, cont.

- The periods of revolution were longer when the Earth was receding from Jupiter.
  - 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.
  - This was important because it demonstrated that light has a finite speed as well as giving an estimate of that speed.

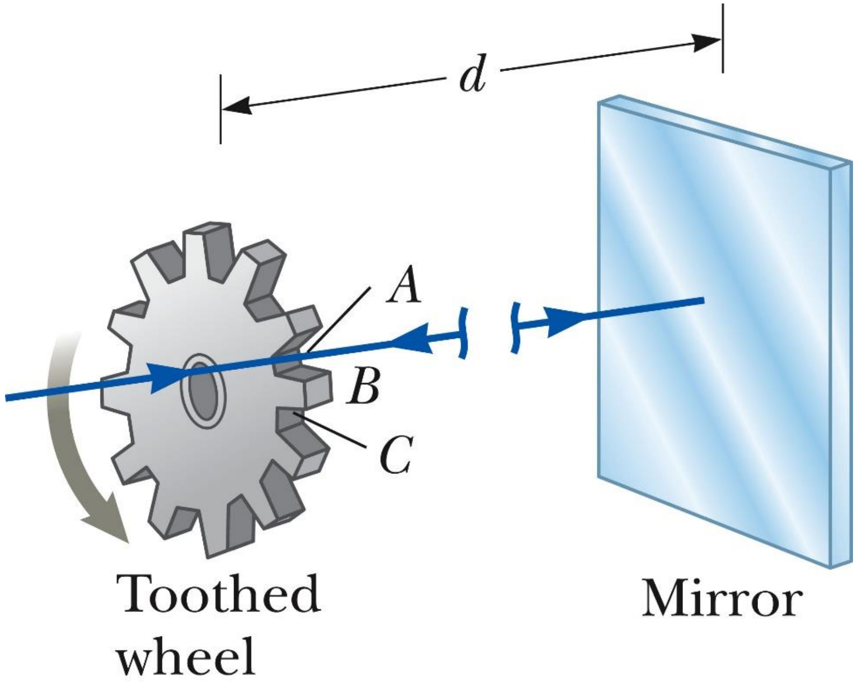
Measurements of the Speed of Light – Fizeau's Method

- This was the first successful method for measuring the speed of light by means of a purely terrestrial technique.
- It was developed in 1849 by Armand Fizeau.
- He used a rotating toothed wheel.
- The distance between the wheel (considered to be the source) and a mirror was known.

Fizeau's Method, cont.

- d is the distance between the wheel and the mirror.
- Δt is the time for one round trip.
- Then $c = 2d / \Delta t$
- Fizeau found a value of

  $c = 3.1 \times 10^8$ m/s.



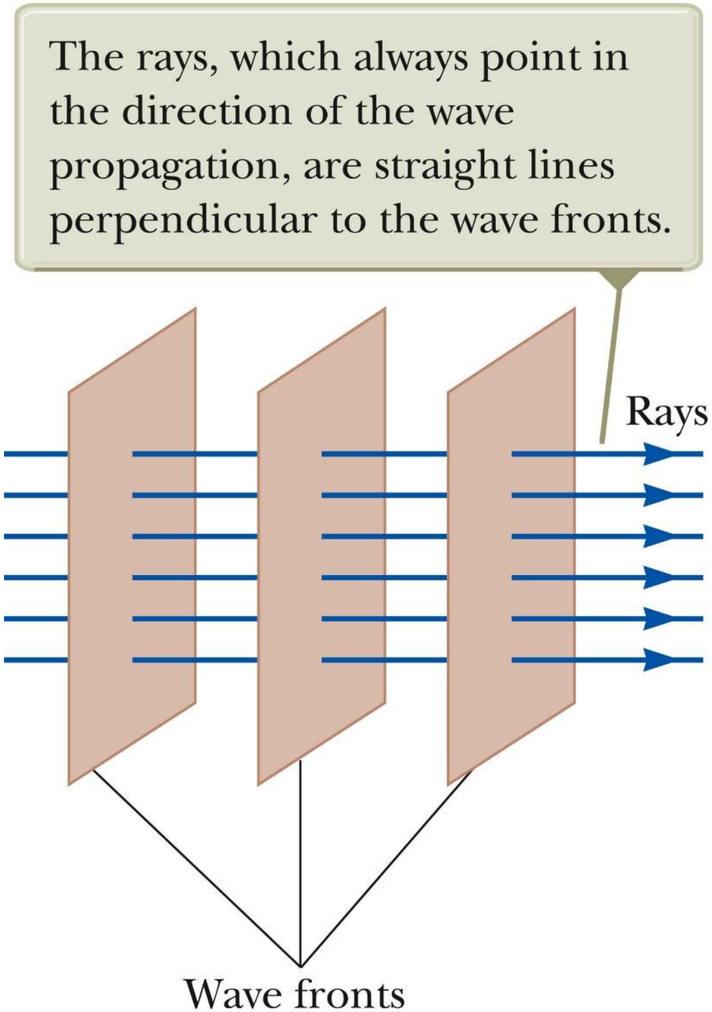
The Ray Approximation in Ray Optics

- **Ray optics** (sometimes called *geometric* optics) involves the study of the propagation of light.
- It uses the assumption that light travels in a straight-line path in a uniform medium and changes its direction when it meets the surface of a different medium or if the optical properties of the medium are nonuniform.
- The ray approximation is used to represent beams of light.

Section 35.3

Ray Approximation

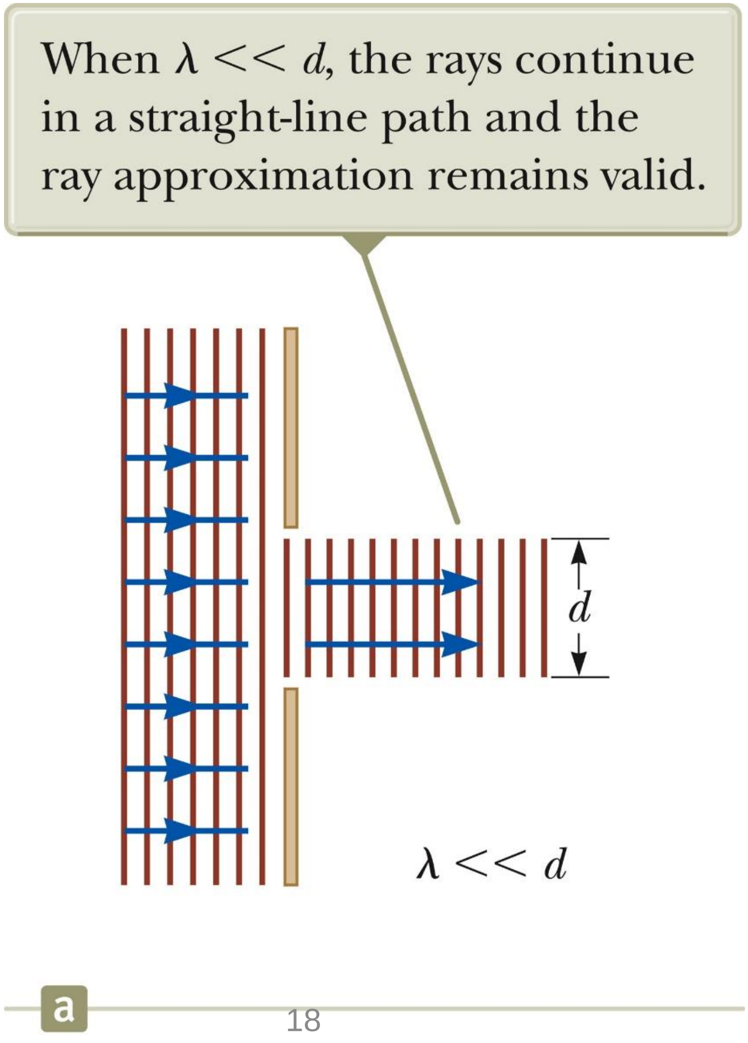
- The rays are straight lines perpendicular to the wave fronts.
- With the ray approximation, we assume that a wave moving through a medium travels in a straight line in the direction of its rays.



Section 35.3

Ray Approximation, cont.

- If a wave meets a barrier, with $\lambda << d$, the wave emerging from the opening continues to move in a straight line.
  - d is the diameter of the opening.
  - There may be some small edge effects.
- This approximation is good for the study of mirrors, lenses, prisms, etc.
- Other effects occur for openings of other sizes.
  - See fig. 35.4 b and c



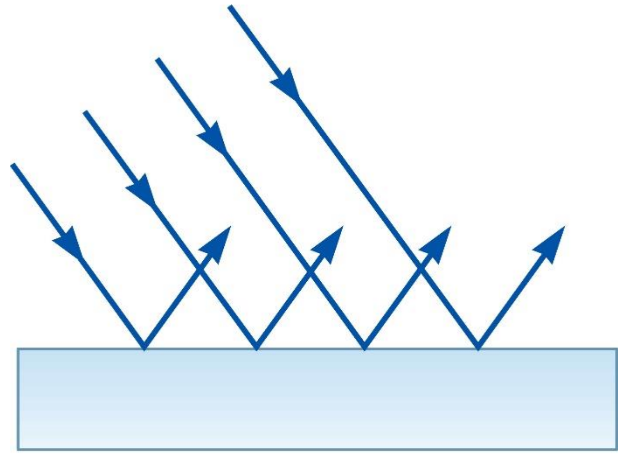
Reflection of Light

- A ray of light, the *incident ray*, travels in a medium.
- When it encounters a boundary with a second medium, part of the incident ray is reflected back into the first medium.
  - This means it is directed backward into the first medium.
- For light waves traveling in three-dimensional space, the reflected light can be in directions different from the direction of the incident rays.

Section 35.4

Specular Reflection

- *Specular reflection* is reflection from a smooth surface.
- The reflected rays are parallel to each other.
- All reflection in this text is assumed to be specular.



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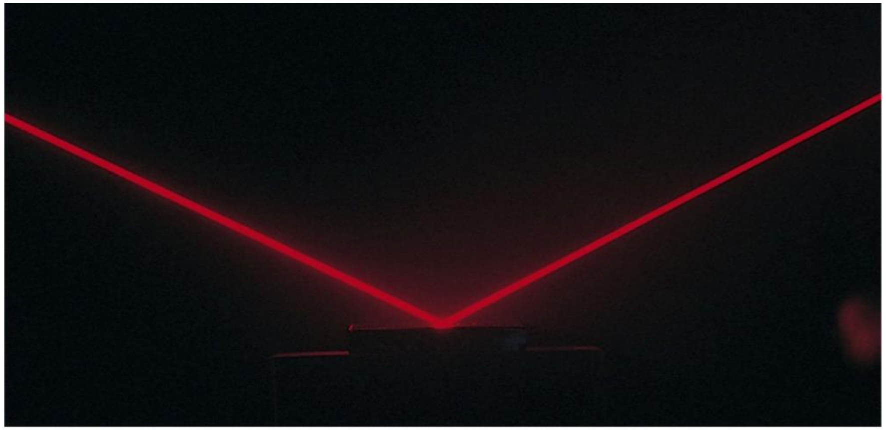

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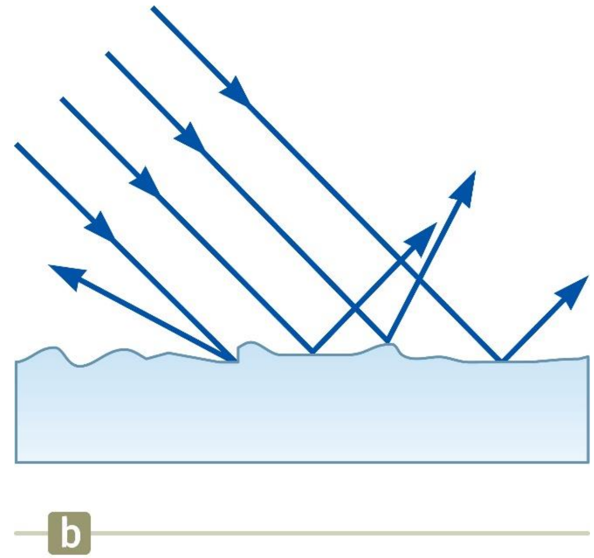
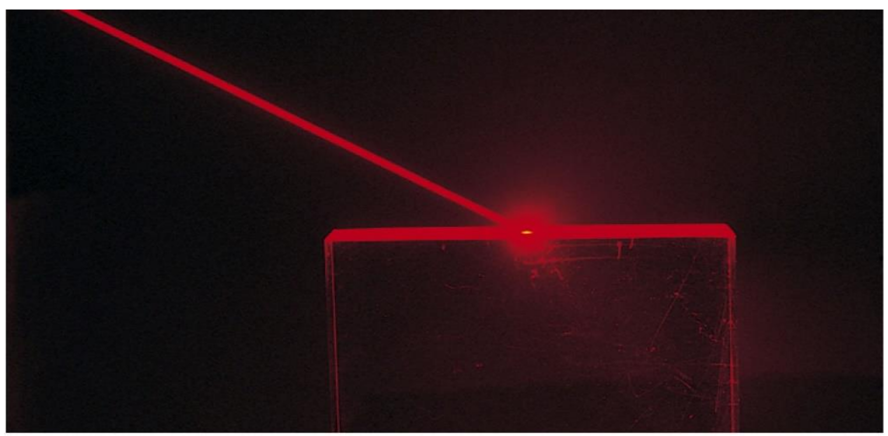
Section 35.4

Diffuse Reflection

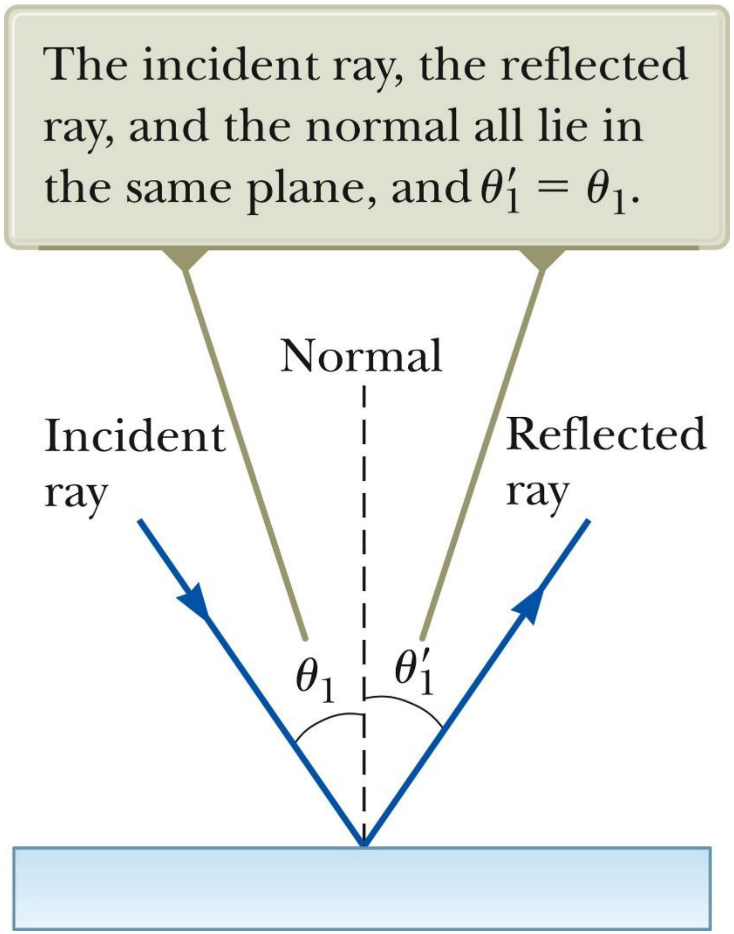
- *Diffuse reflection* is reflection from a rough surface.
- The reflected rays travel in a variety of directions.
- A surface behaves as a smooth surface as long as the surface variations are much smaller than the wavelength of the light.





Law of Reflection

- The *normal* is a line perpendicular to the surface.
  - It is at the point where the incident ray strikes the surface.
- The incident ray makes an angle of θ_1 with the normal.
- The reflected ray makes an angle of θ_1' with the normal.



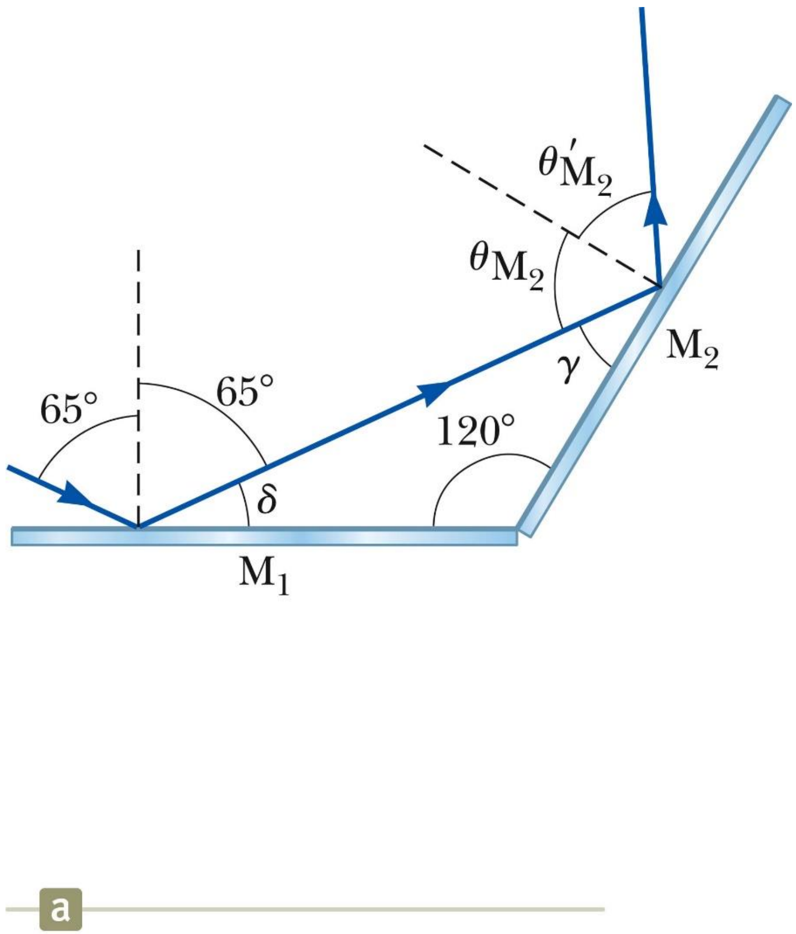
Law of Reflection, cont.

- The angle of reflection is equal to the angle of incidence.
- $\theta_1' = \theta_1$
  - This relationship is called the Law of Reflection.
- The incident ray, the reflected ray and the normal are all in the same plane.
- Because this situation happens often, an analysis model, *wave under reflection*, is identified.
- Notation note:
  - The subscript 1 refers to parameters for the light in the first medium.
  - If light travels in another medium, the subscript 2 will be associated with the new medium.
- Since reflection of waves is a common phenomena, we identify an analysis model for this situation, the ***wave under reflection analysis model.***

Section 35.4

Multiple Reflections

- The incident ray strikes the first mirror.
- The reflected ray is directed toward the second mirror.
- There is a second reflection from the second mirror.
- Apply the Law of Reflection and some geometry to determine information about the rays.



Retro reflection

- Assume the angle between two mirrors is 90^o *.*
- The reflected beam returns to the source parallel to its original path.
- This phenomenon is called *retroreflection.*
- Applications include:
  - Measuring the distance to the Moon
  - Automobile taillights
  - Traffic signs

Section 35.4

Refraction of Light

- When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, part of the energy is reflected and part enters the second medium.
- The ray that enters the second medium changes its direction of propagation at the boundary.
  - This bending of the ray is called *refraction.*

Section 35.5

Refraction, cont.

- The incident ray, the reflected ray, the refracted ray, and the normal all lie on the same plane.
- The angle of refraction depends upon the material and the angle of incidence.

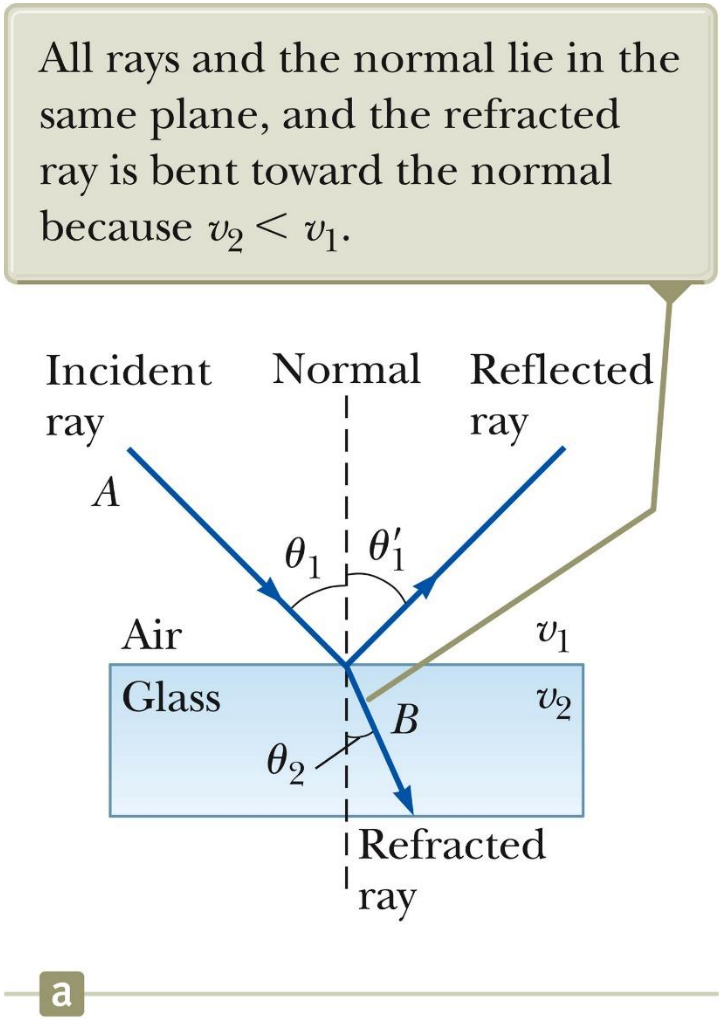
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

  – v_1 is the speed of the light in the first medium and v_2 is its speed in the second.

Section 35.5

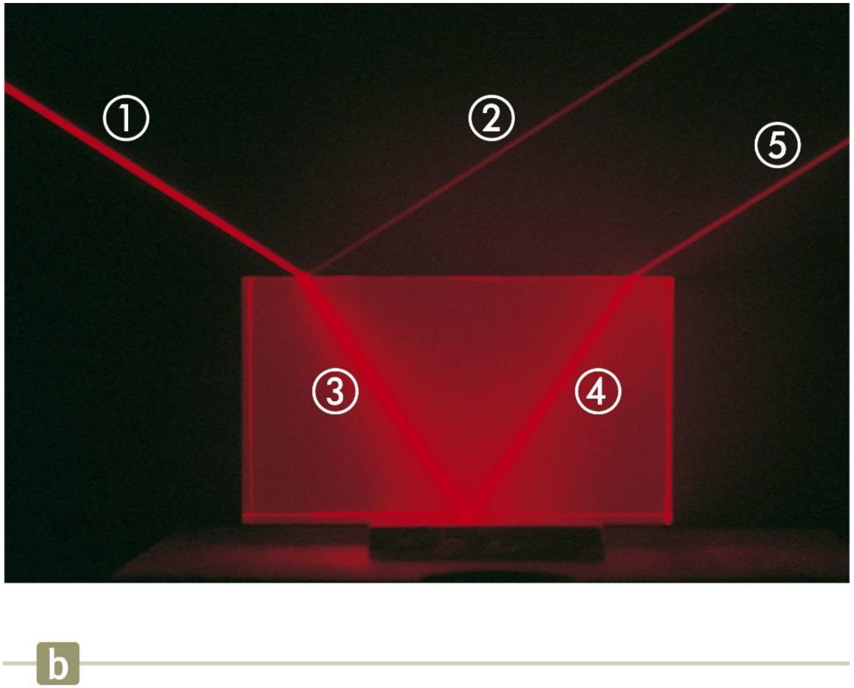
Refraction of Light, final

- The path of the light through the refracting surface is reversible.
  - For example, a ray travels from A to B.
  - If the ray originated at B, it would follow the line AB to reach point A.



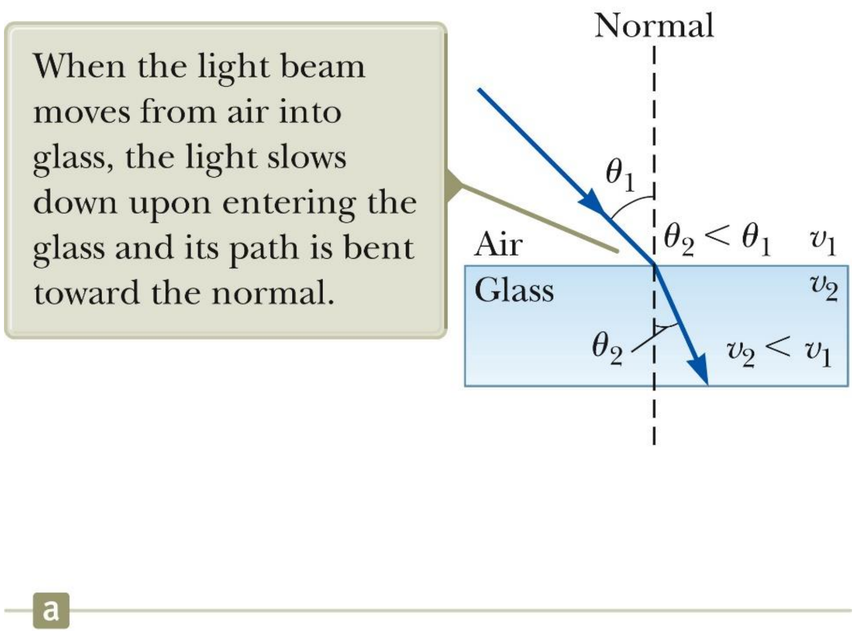
Following the Reflected and Refracted Rays

- Ray ① is the incident ray.
- Ray ② is the reflected ray.
- Ray ③ is refracted into the lucite.
- Ray ④ is internally reflected in the lucite.
- Ray ⑤ is refracted as it enters the air from the lucite.



Refraction Details, 1

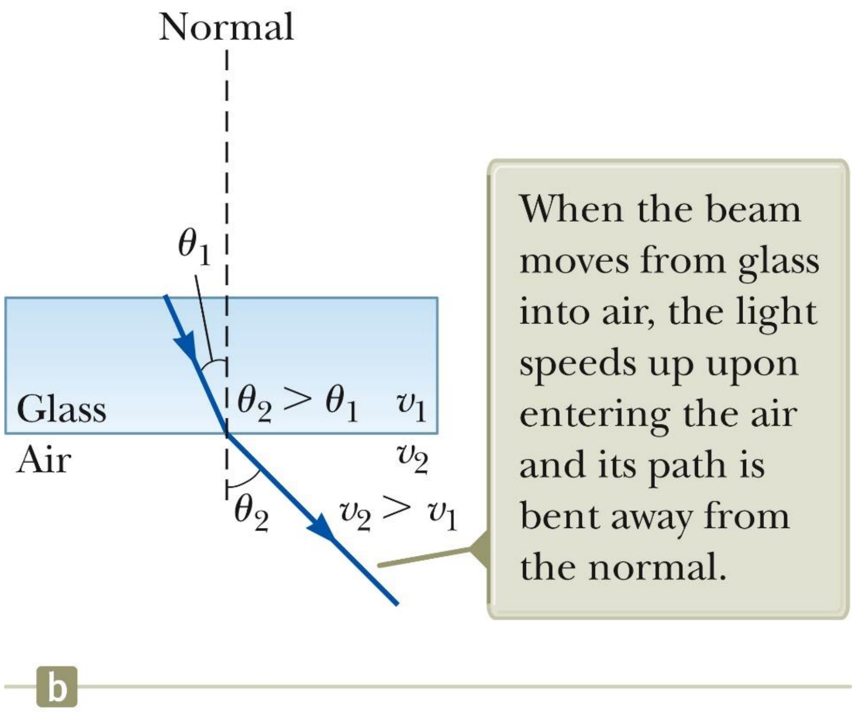
- Light may refract into a material where its speed is lower.
- The angle of refraction is less than the angle of incidence.
  - The ray bends *toward* the normal.



Section 35.5

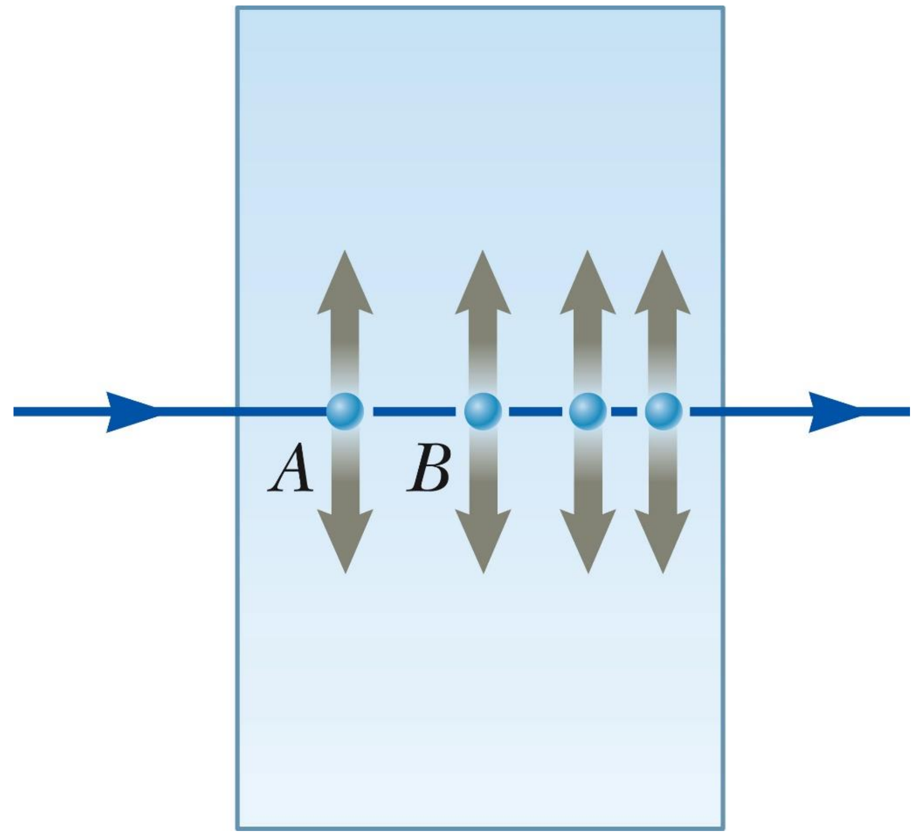
Refraction Details, 2

- Light may refract into a material where its speed is higher.
- The angle of refraction is greater than the angle of incidence.
  - The ray bends *away from* the normal.



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.



Section 35.5

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

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

Index of Refraction, cont.

- For a vacuum, n = 1
  - We assume n = 1 for air also
- For other media, n > 1
- n is a dimensionless number greater than unity.
  - n is not necessarily an integer.

Section 35.5

Some Indices of Refraction

TABLE 35.1 *Indices of Refraction*

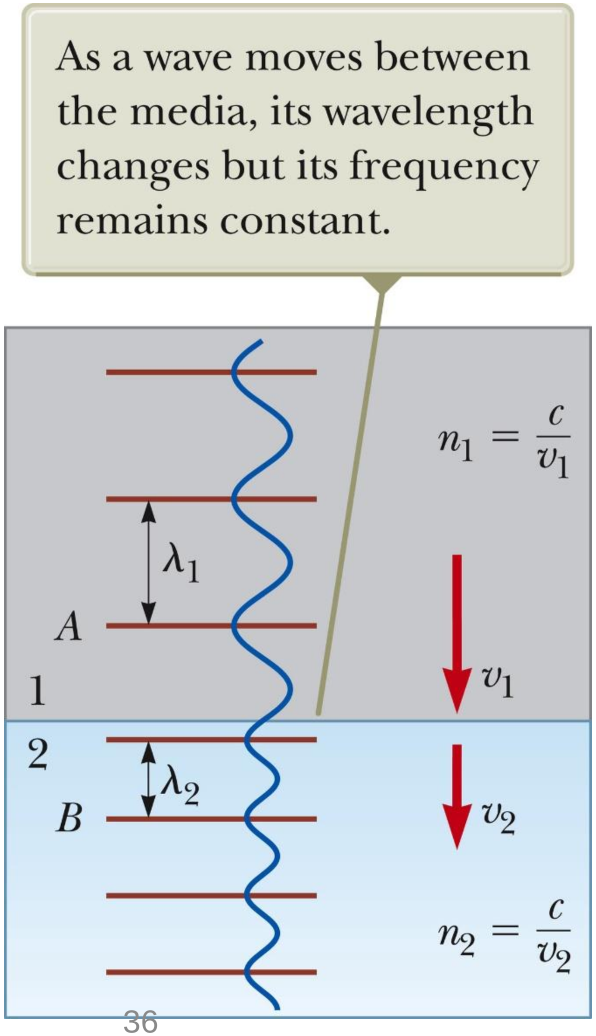
Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
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

Note: All values are for light having a wavelength of 589 nm in vacuum.

Section 35.5

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 they created or destroyed at the boundary, so ƒ must stay the same.



Index of Refraction Extended

- 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 of the two media can be expressed as various ratios.

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

- The index of refraction is inversely proportional to the wave speed.
  - As the wave speed decreases, the index of refraction increases.
  - The higher the index of refraction, the more it slows downs the light wave speed.

Section 35.5

More About Index of Refraction

- The previous relationship can be simplified to compare wavelengths and indices: $\lambda_1 n_1 = \lambda_2 n_2$
- In air, $n_1 = 1$ and the index of refraction of the material can be defined in terms of the wavelengths.

$$n = \frac{\lambda}{\lambda_n} \quad \left(\frac{\lambda \text{ in vacuum}}{\lambda \text{ in a medium}} \right)$$

Section 35.5

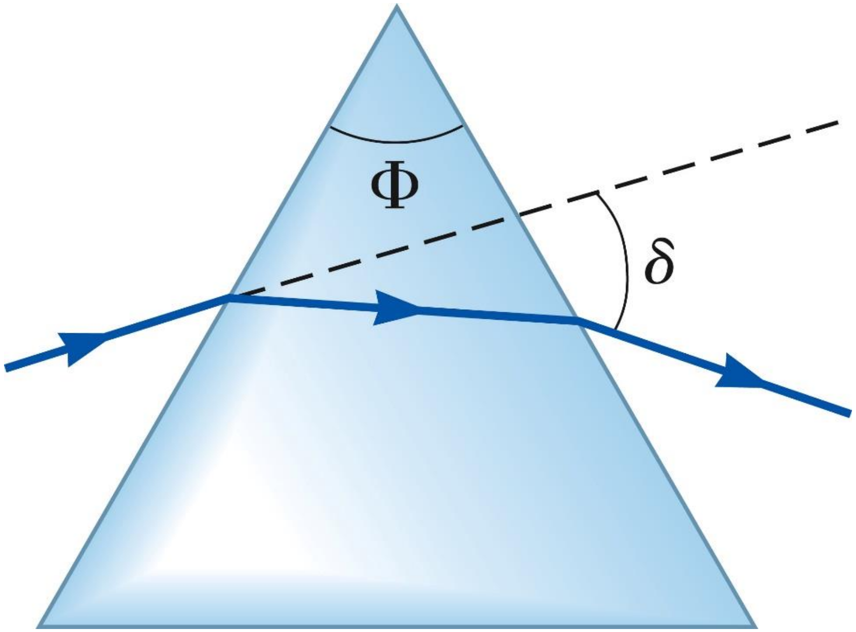
Snell's Law of Refraction

- $n_1 \sin \theta_1 = n_2 \sin \theta_2$
  - θ_1 is the angle of incidence
  - θ_2 is the angle of refraction
- The experimental discovery of this relationship is usually credited to Willebrord Snell and is therefore known as **Snell's law of refraction.**
- Refraction is a commonplace occurrence, so identify an analysis model as a **wave under refraction.**

Section 35.5

Prism

- A ray of single-wavelength light incident on the prism will emerge at angle δ from its original direction of travel.
  - δ is called the **angle of deviation.**
  - Φ is the apex angle.



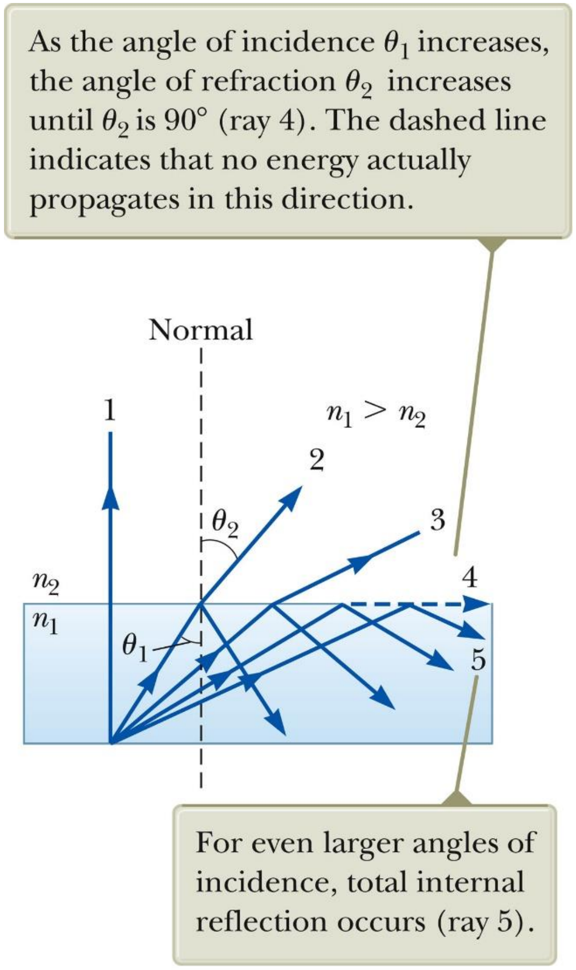
Total Internal Reflection

- 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.

Section 35.8

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 $n_1 > n_2$.



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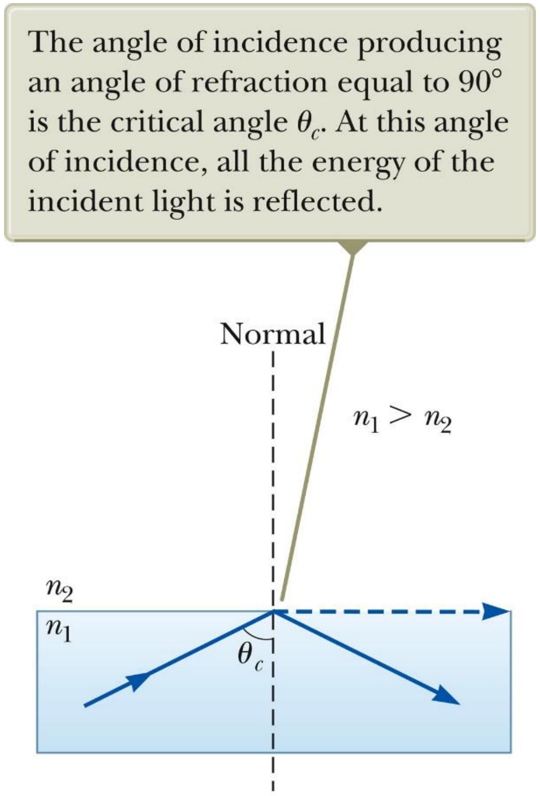
Critical Angle

- 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}.

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



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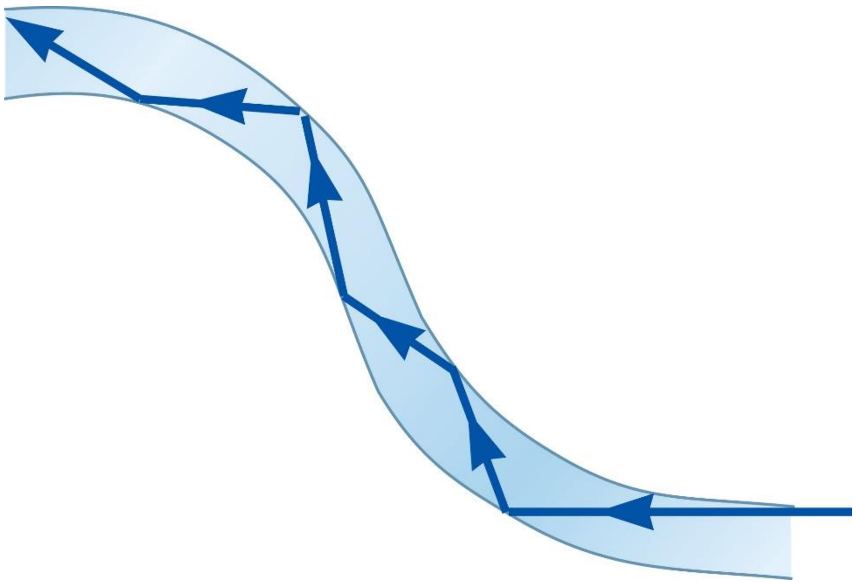
Critical Angle, cont.

- For angles of incidence *greater* than the critical angle, the beam is entirely reflected at the boundary.
  - This ray obeys the law of reflection at the boundary.
- Total internal reflection occurs only when light is directed from a medium of a given index of refraction toward a medium of lower index of refraction.

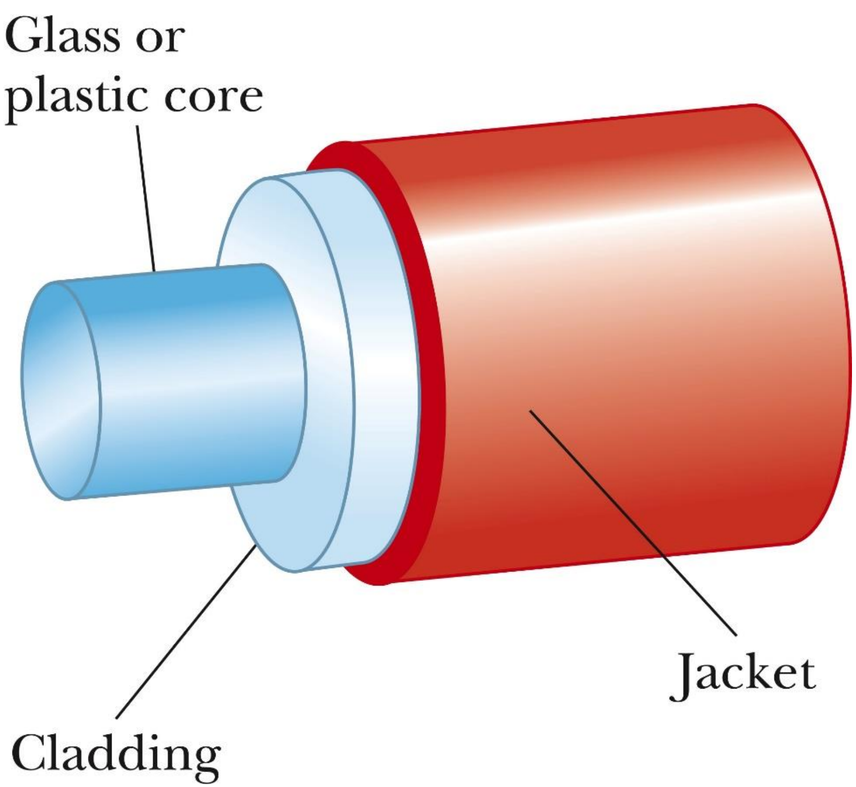
Fiber Optics

- An application of internal reflection
- Plastic or glass rods are used to “pipe” light from one place to another.
- Applications include:
  - Medical examination of internal organs
  - Telecommunications



Construction of an Optical Fiber

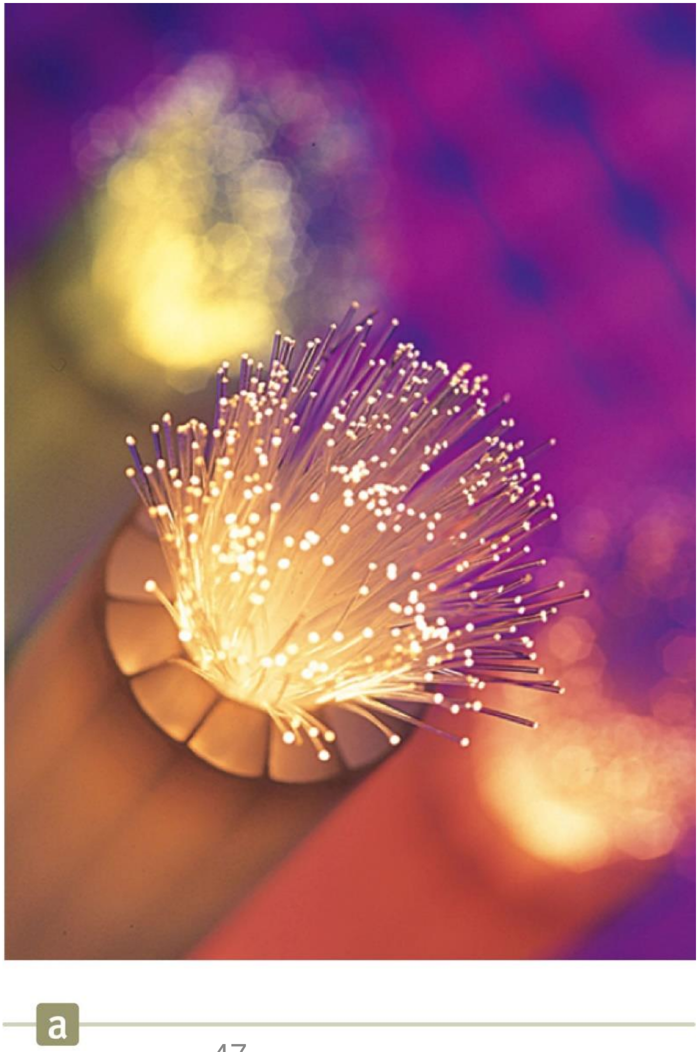
- The transparent core is surrounded by *cladding.*
  - The cladding has a lower *n* than the core.
  - This allows the light in the core to experience total internal reflection.
- The combination is surrounded by the jacket.



Section 35.8

Fiber Optics, cont.

- A flexible light pipe is called an **optical fiber.**
- A bundle of parallel fibers (shown) can be used to construct an optical transmission line.



Section 35.8

Summary الخلاصة

Law of Reflection.
The angle of reflection is equal to the angle of incidence. $\theta_1' = \theta_1$

Snell's Law of Refraction

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

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

Total Internal Reflection

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

Thank You

ACKNOWLEDGEMENTS