Chapter 35

The Nature of Light and the Laws of Geometric Optics

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.

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.

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 because there was no conceivable way in which two or more particles could come together and cancel one another.

Maxwell asserted that light was a form of high-frequency electromagnetic wave.

Hertz confirmed Maxwell's predictions.

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.
- The energy of a photon is proportional to the frequency of the electromagnetic wave:
- $E = hf$
  - h is Planck's Constant and = 6.63×10^{-34} J·s

Example

Find the energy of (a) a photon having a frequency of 5.00 × 10^{17} Hz and (b) a photon having a wavelength of 3.00 × 10^{2} nm. Express your answers in units of electron volts, noting that 1 eV = 1.60 × 10^{-19} J. h = 6.63 x 10^{-34} J.s

We find the energy of the photons from $E = hf$.

$$E = hf = \left(6.63\times10^{-34}\ \mathrm{J\cdot s}\right)\left(5.00\times10^{17}\ \mathrm{Hz}\right)\left(\frac{1\ \mathrm{eV}}{1.60\times10^{-19}\ \mathrm{J}}\right)$$

$$= \boxed{2.07\times10^{3}\ \mathrm{eV}} = 2.07\ \mathrm{keV}$$

$$E = hf = \frac{hc}{\lambda}$$

$$= \frac{\left(6.63\times10^{-34}\ \mathrm{J\cdot s}\right)\left(3.00\times10^{8}\ \mathrm{m/s}\right)}{3.00\times10^{2}\ \mathrm{nm}}\left(\frac{1\ \mathrm{nm}}{10^{-9}\ \mathrm{m}}\right)\left(\frac{1\ \mathrm{eV}}{1.60\times10^{-19}\ \mathrm{J}}\right)$$

$$= \boxed{4.14\ \mathrm{eV}}$$

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.

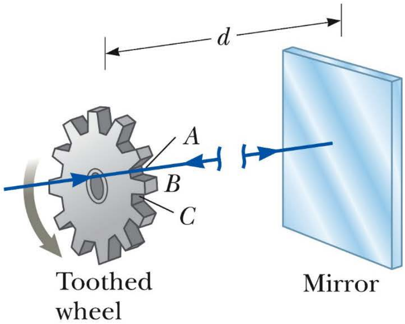
Measurements of the Speed of Light – Fizeau's Method

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.



The Ray Approximation in Ray Optics

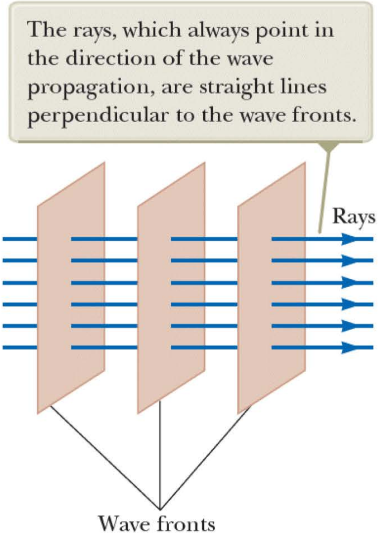
Ray optics (sometimes called *geometric* optics) involves the study of the propagation of light.

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.

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.



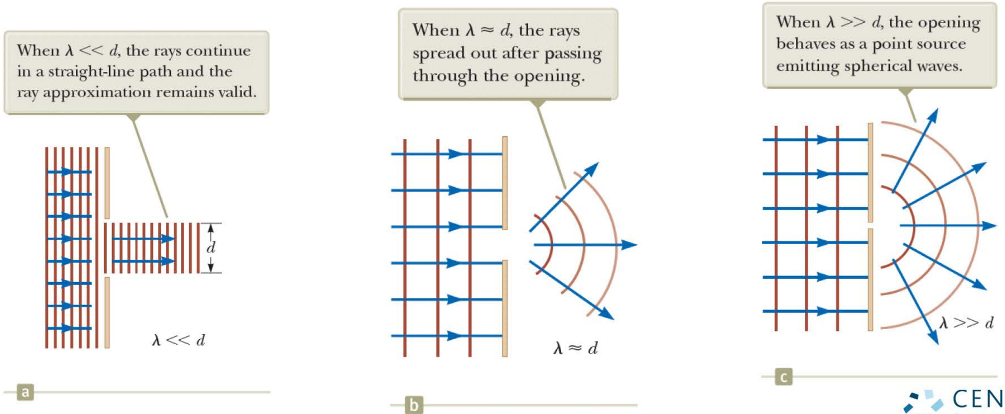
Ray Approximation, cont.

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.



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.

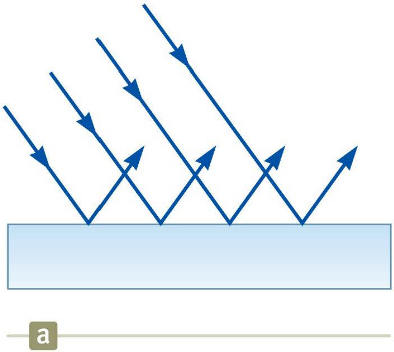
For light waves traveling in three-dimensional space, the reflected light can be in directions different from the direction of the incident rays.

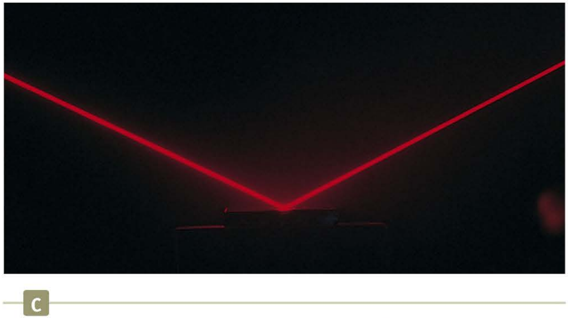
Specular Reflection

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.



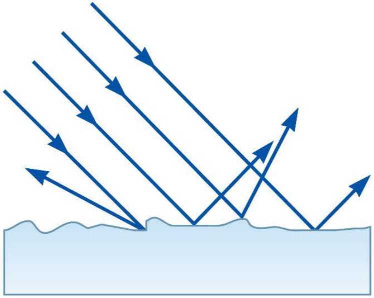


Diffuse Reflection

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.



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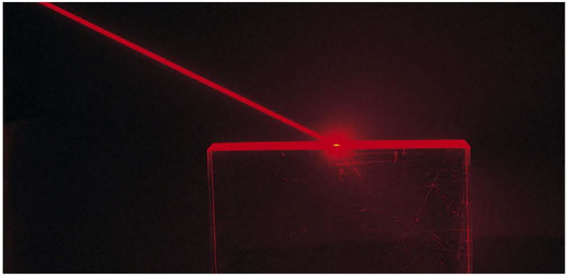

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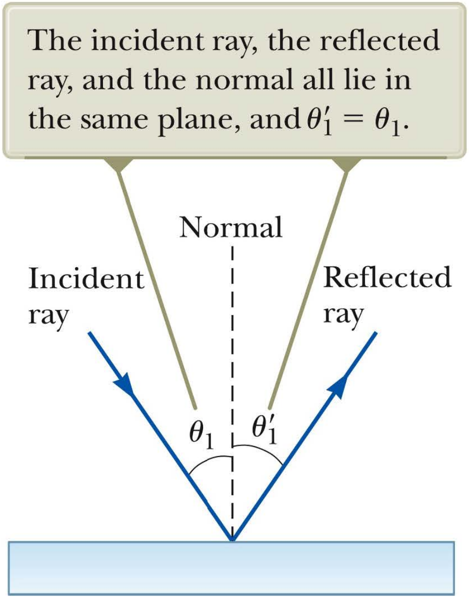
Law of Reflection

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.

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.***

The Double-Reflected Light Ray, Example

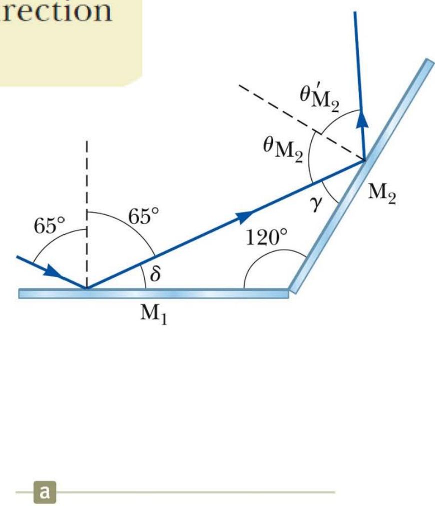
Two mirrors make an angle of 120° with each other as illustrated in Figure 35.7a. A ray is incident on mirror M_1 at an angle of 65° to the normal. Find the direction of the ray after it is reflected from mirror M_2.

$$\delta = 90° - 65° = 25°$$

$$\gamma = 180° - 25° - 120° = 35°$$

$$\theta_{M_2} = 90° - 35° = 55°$$

$$\theta'_{M_2} = \theta_{M_2} = \boxed{55°}$$



Retroreflection

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

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.*

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.

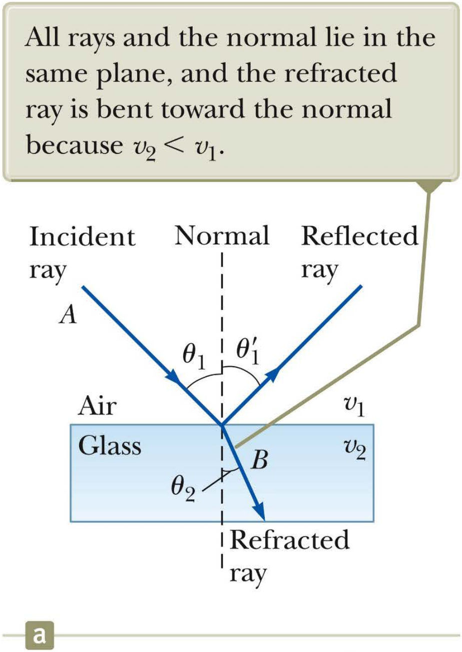
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

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

Refraction of Light, cont'd

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

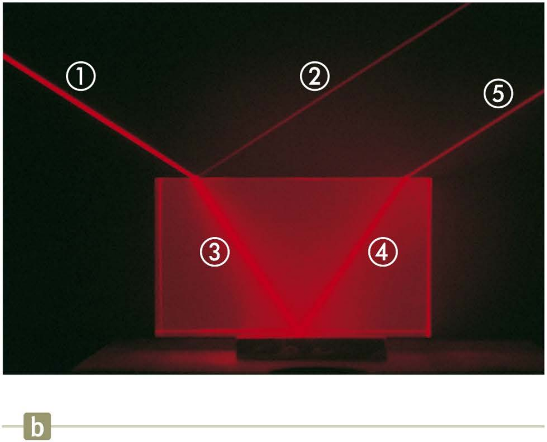
Ray ① is the incident ray.

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.

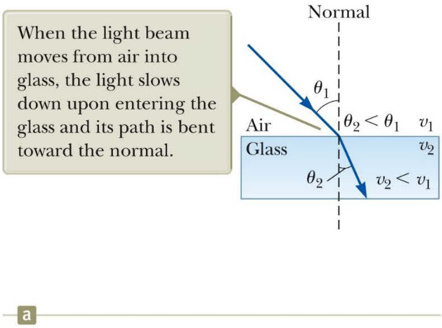


Refraction Details

Light may refract into a material where its speed is lower.

The angle of refraction is less than the angle of incidence.

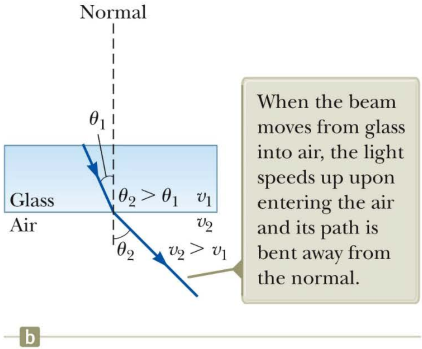
- The ray bends *toward* the normal.



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.



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

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

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.

Some Indices of Refraction

TABLE 35.1 *Indices of Refraction*

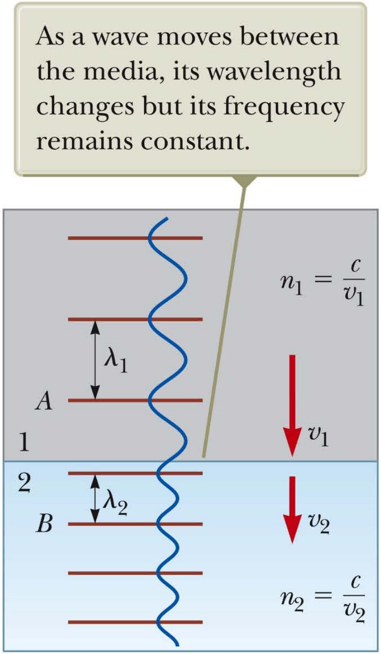
Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473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

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 *f* 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.

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.

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

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 common place occurrence, so identify an analysis model as a **wave under refraction.**

Example

The wavelength of red helium–neon laser light in air is 632.8 nm. (a) What is its frequency? (b) What is its wavelength in glass that has an index of refraction of 1.50? (c) What is its speed in the glass?

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^{8}\ \text{m/s}}{6.328 \times 10^{-7}\ \text{m}} = \boxed{4.74 \times 10^{14}\ \text{Hz}}$$

$$\lambda_{\text{glass}} = \frac{\lambda_{\text{air}}}{n} = \frac{632.8\ \text{nm}}{1.50} = \boxed{422\ \text{nm}}$$

$$v_{\text{glass}} = \frac{c_{\text{air}}}{n} = \frac{3.00 \times 10^{8}\ \text{m/s}}{1.50} = \boxed{2.00 \times 10^{8}\ \text{m/s}}$$

Example

A ray of light is incident on a flat surface of a block of crown glass that is surrounded by water. The angle of refraction is 19.6° . Find the angle of reflection.

We find the angle of incidence from Snell's law, $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Solving,

$$1.333 \sin\theta_1 = 1.52 \sin 19.6° \quad \rightarrow \quad \theta_1 = 22.5°$$

The angle of reflection of the beam in water is then also $\boxed{22.5°}$.

Example

A light ray initially in water enters a transparent substance at an angle of incidence of 37.0°, and the transmitted ray is refracted at an angle of 25.0°. Calculate the speed of light in the transparent substance.

From the wave under refraction model,

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

$$n_2 = \frac{1.333 \sin 37.0°}{\sin 25.0°} = 1.90$$

Then, from the definition of index of refraction,

$$n_2 = 1.90 = \frac{c}{v}: \qquad v = \frac{c}{1.90} = 1.58 \times 10^8 \text{ m/s} = \boxed{158 \text{ Mm/s}}$$

Dispersion

For a given material, the index of refraction varies with the wavelength of the light passing through the material.

This dependence of n on λ is called dispersion.

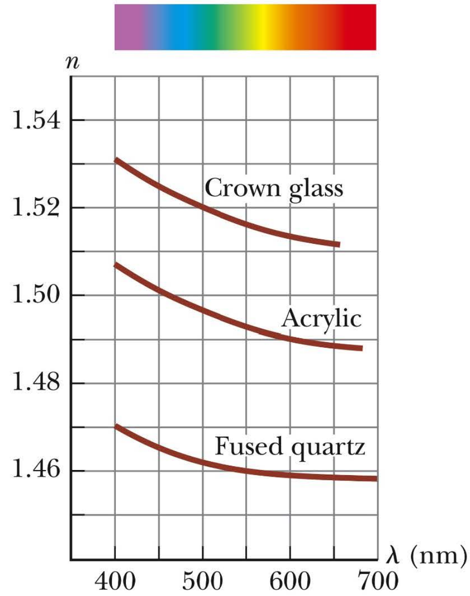
Snell's law indicates light of different wavelengths is bent at different angles when incident on a refracting material.

$$\frac{\lambda_1}{\lambda_2} = \frac{n_2}{n_1}$$

Variation of Index of Refraction with Wavelength

The index of refraction for a material generally decreases with increasing wavelength.

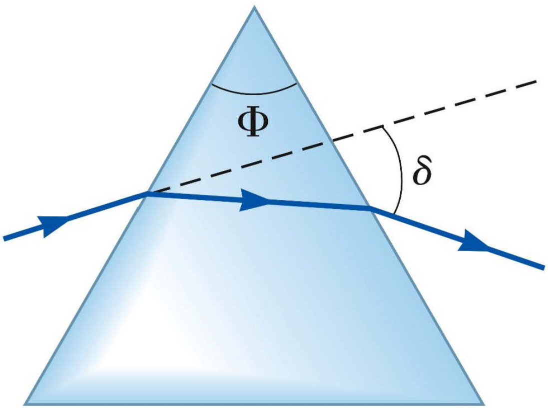
Violet light bends more than red light when passing into a refracting material.



Prism

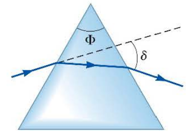
A ray of single-wavelength light incident on the prism will emerge at angle δ from its original direction of travel.

- δ is called the **angle of deviation.**
- Φ is the apex angle.



Refraction in a Prism

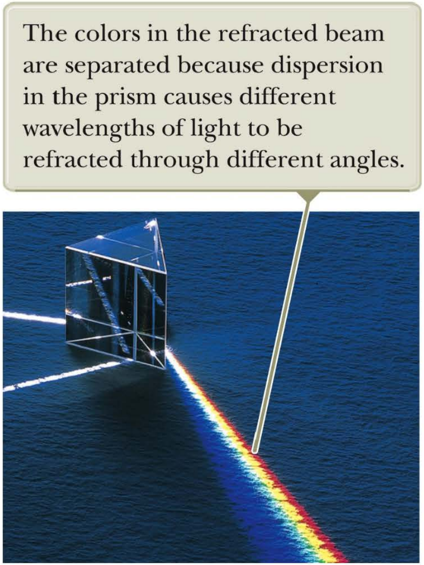
A beam of white light (a combination of all visible wavelengths) is incident on a prism.



The angle of deviation δ depends on wavelength. The rays that emerge spread out in a series of colors known as the visible spectrum.

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.



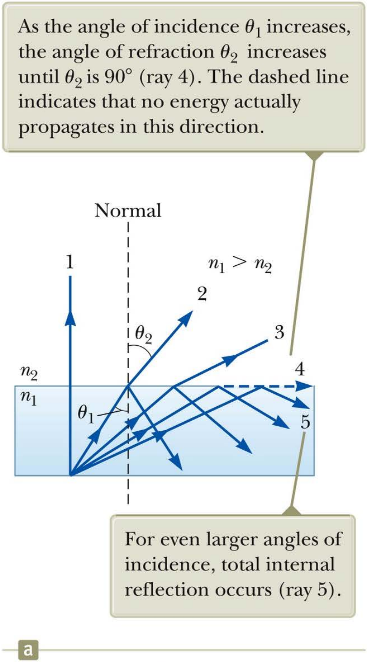
Total Internal Reflection

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,* $\theta_{C.}$

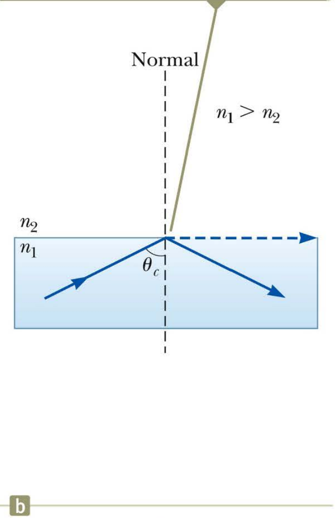
$$\sin \theta_C = \frac{n_2}{n_1} \quad (\text{for } n_1 > n_2)$$

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.

The angle of incidence producing an angle of refraction equal to 90° is the critical angle θ_c. At this angle of incidence, all the energy of the incident light is reflected.



Example

A glass optical fiber (n = 1.50) is submerged in water (n = 1.33). What is the critical angle for light to stay inside the fiber?

$$\sin\theta_c = \frac{n_2}{n_1} = \frac{1.33}{1.50} \rightarrow \theta_c = \boxed{62.5°}$$