Chapter 35

The Nature of Light and the Laws of Geometric Optics

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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.

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.
- $E = hf$
  - h is Planck's Constant and = 6.63×10^{-34} J·s

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.

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.

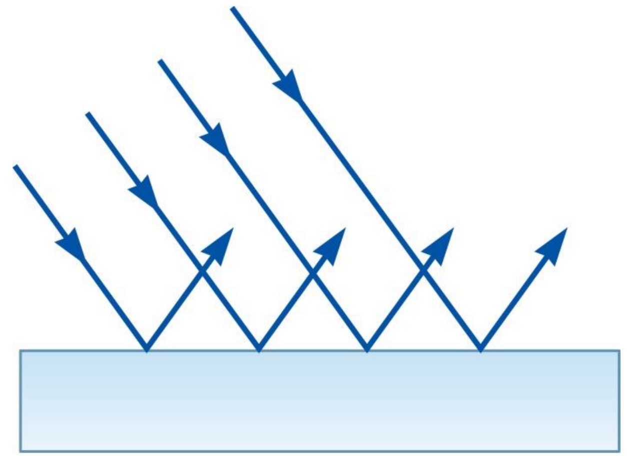
For light waves traveling in three-dimensional space, the reflected light can be in directions different from the direction of the incident rays.

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.



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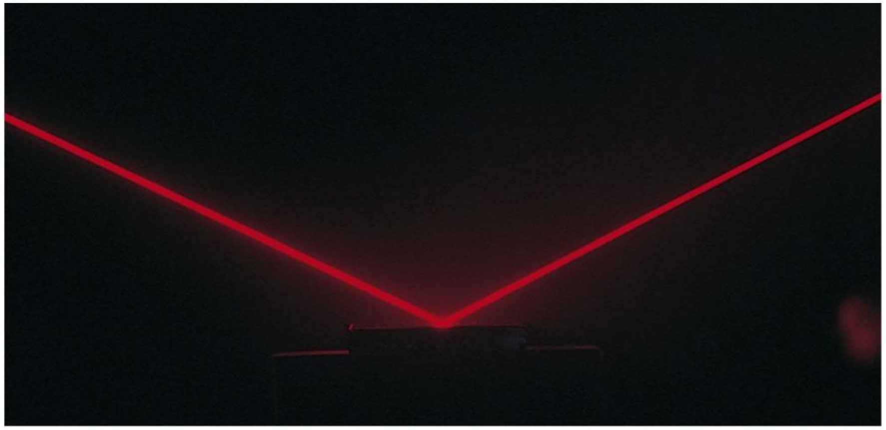

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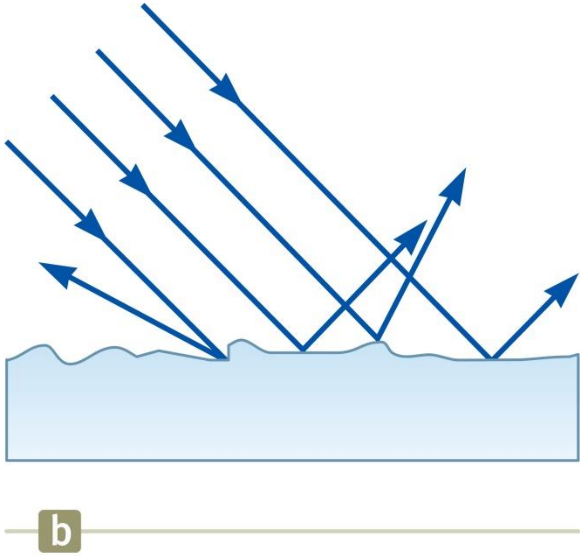
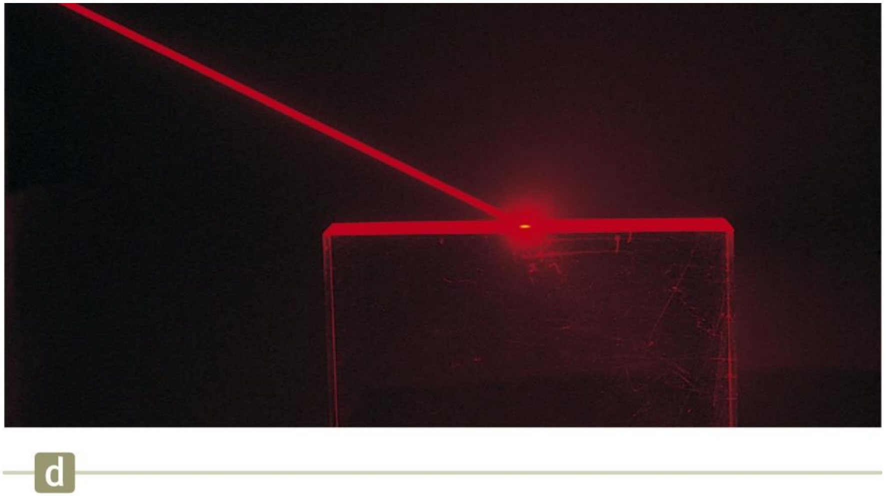
Diffuse Reflection

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.





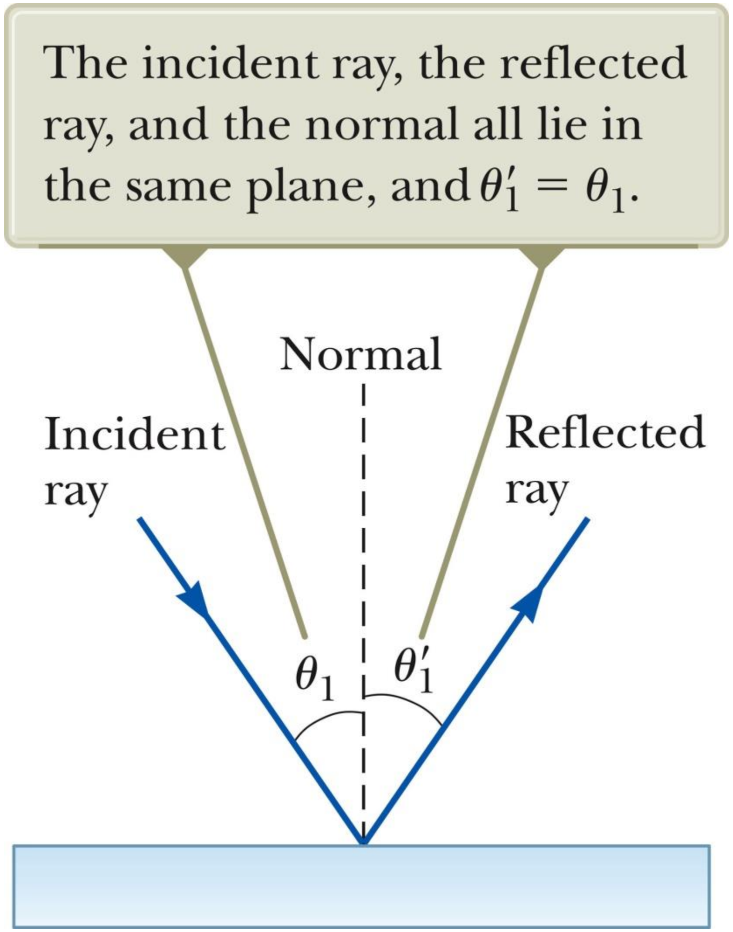
Law of Reflection

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.***

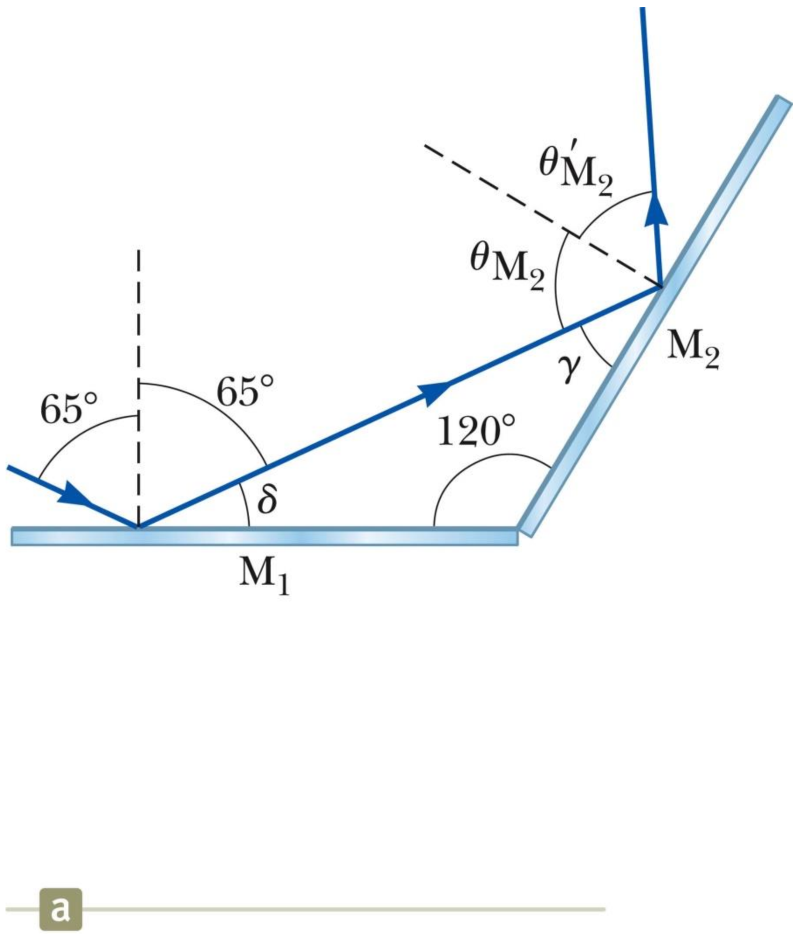
Multiple Reflections

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.



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.*

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.

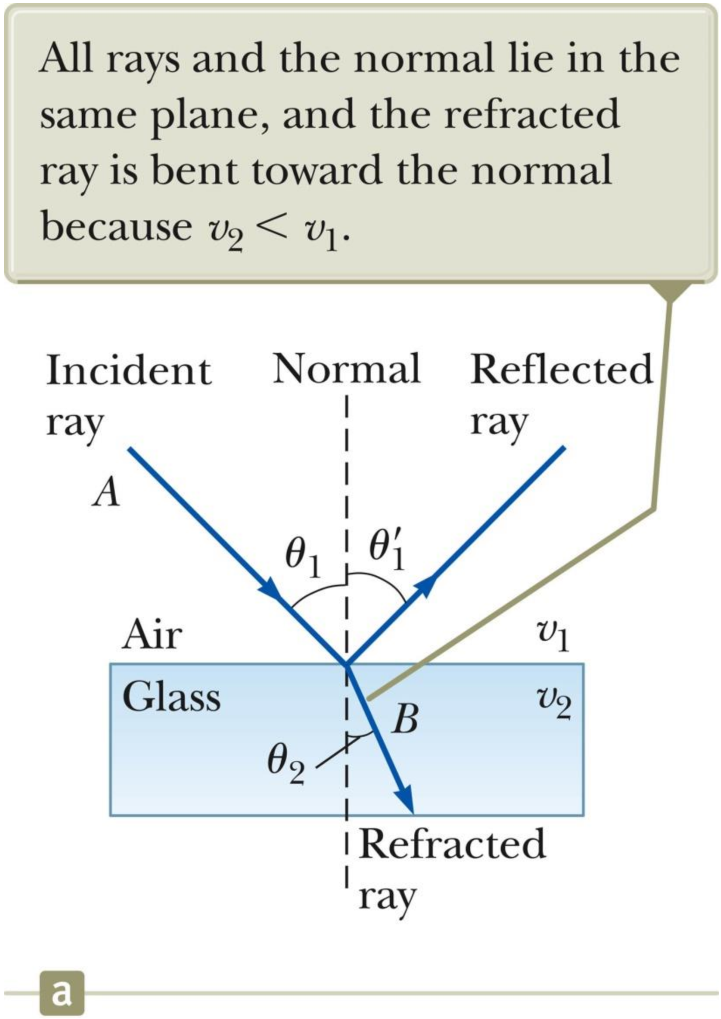
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$$

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

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

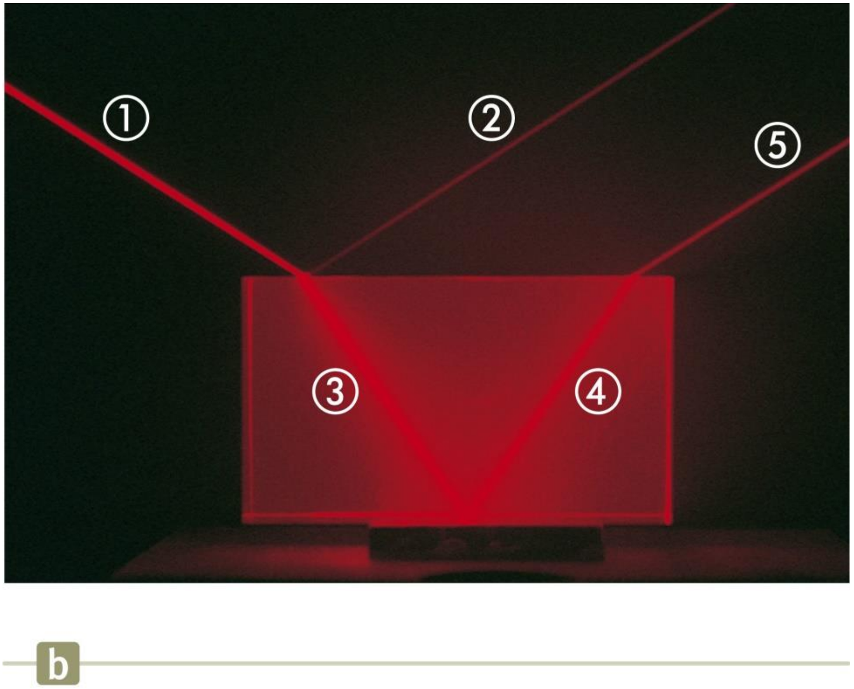
Ray ① is the incident ray.

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.

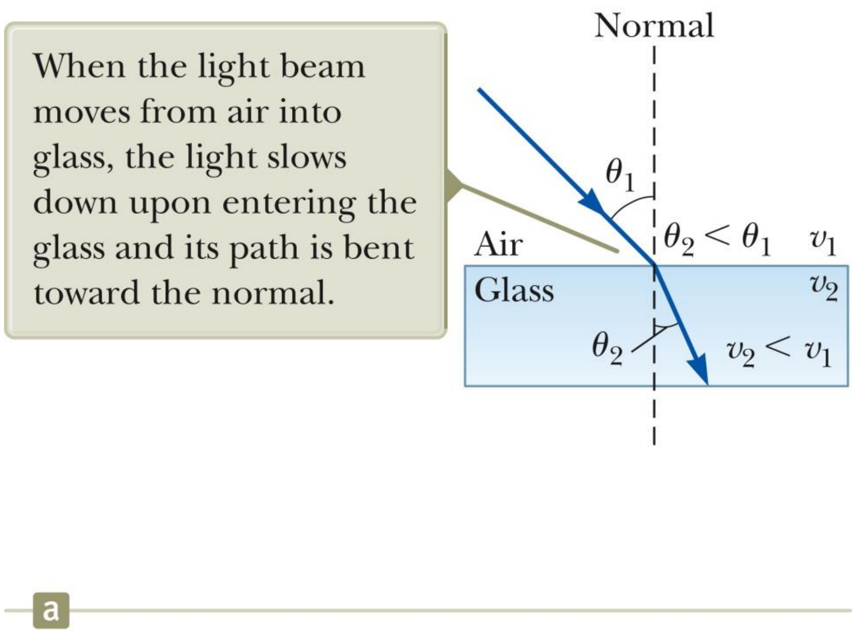


Refraction Details, 1

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.



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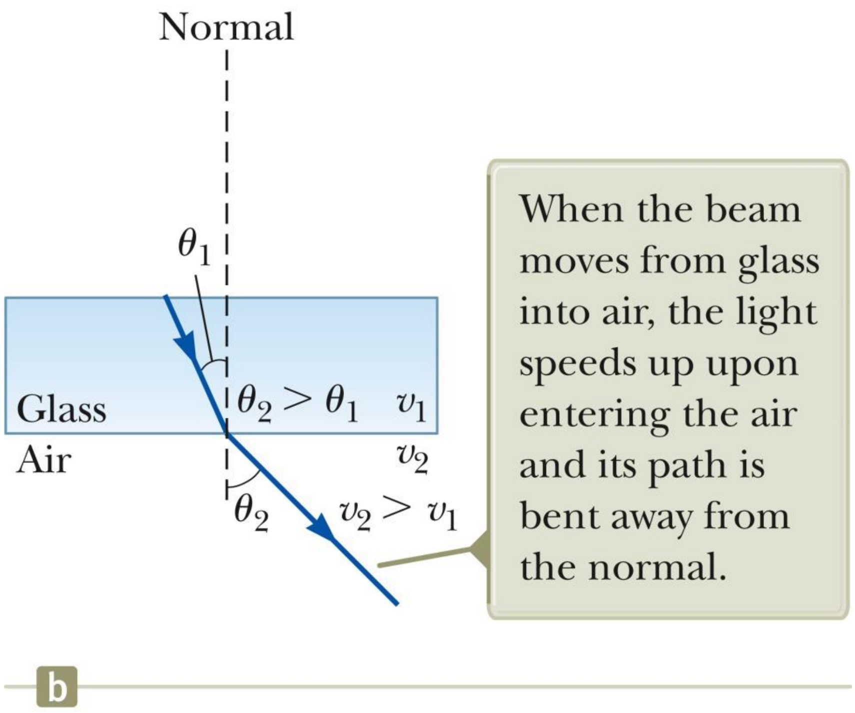
Refraction Details, 2

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.



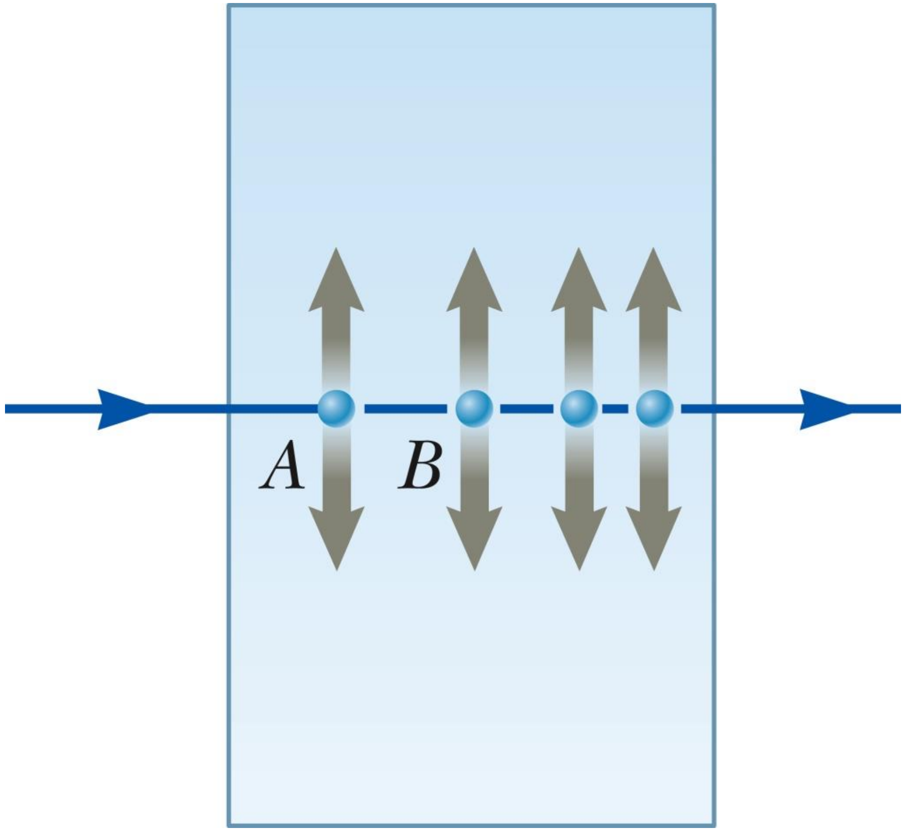
Light in a Medium

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.



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.

Some Indices of Refraction

TABLE 35.1 *Indices of Refraction*

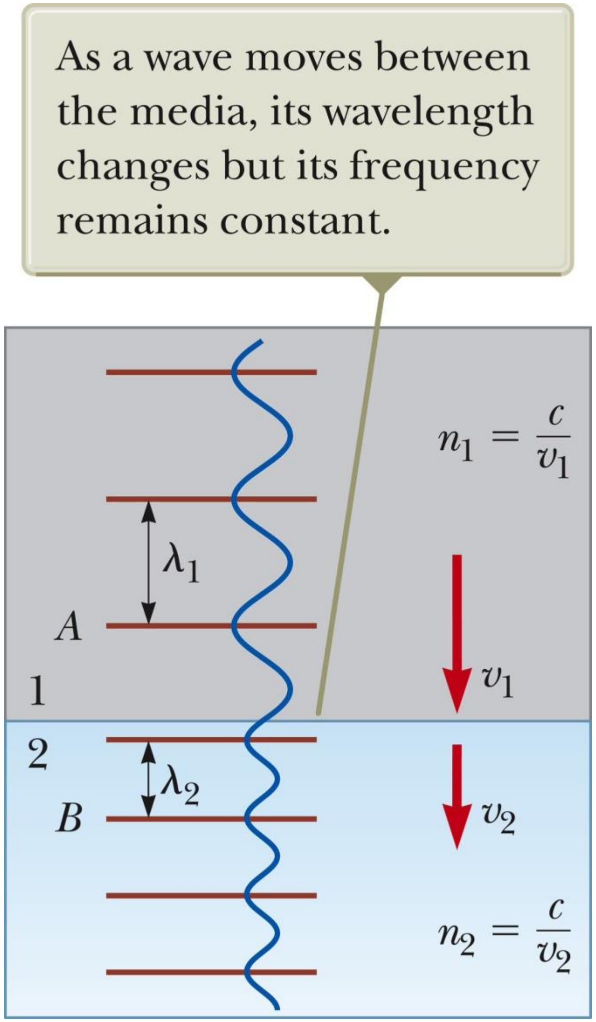
Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473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

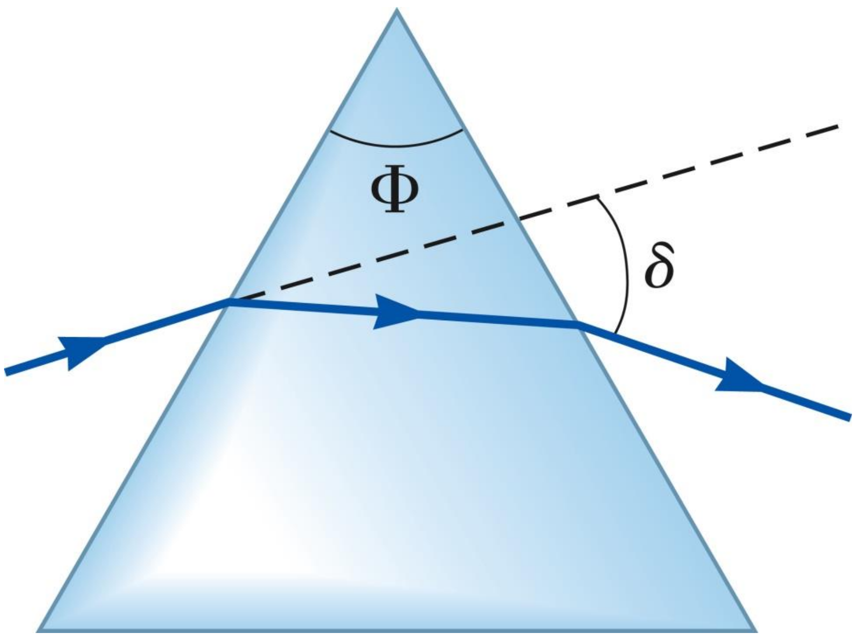
The experimental discovery of this relationship is usually credited to Willebrord Snell and is therefore known as **Snell's law of refraction.**

Refraction is a commonplace occurrence, so identify an analysis model as a **wave under refraction.**

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.



Dispersion

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

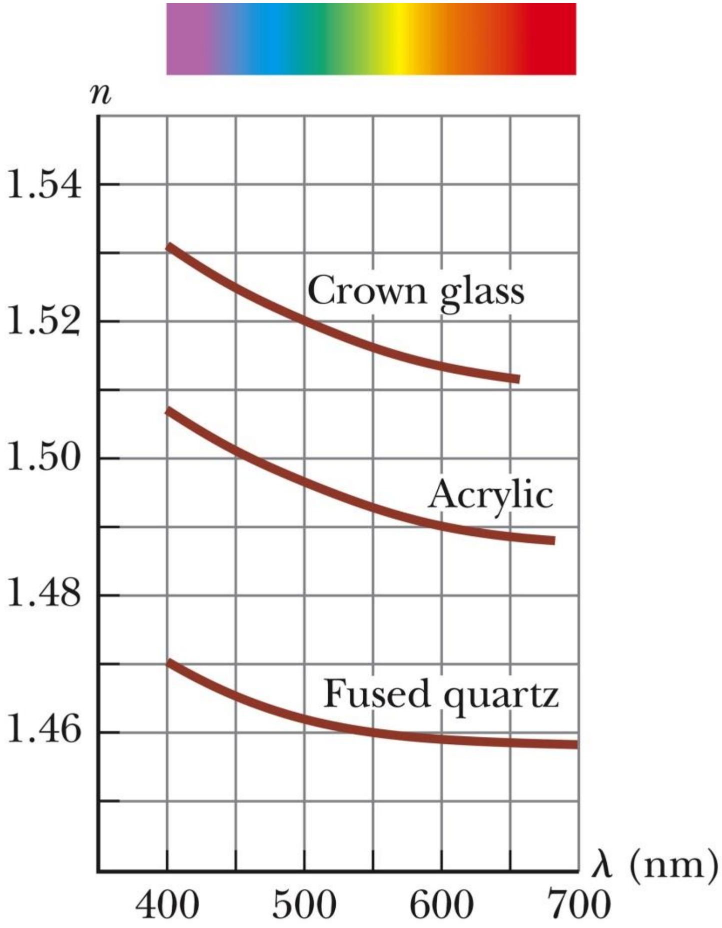
This dependence of n on λ is called dispersion.

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

Variation of Index of Refraction with Wavelength

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

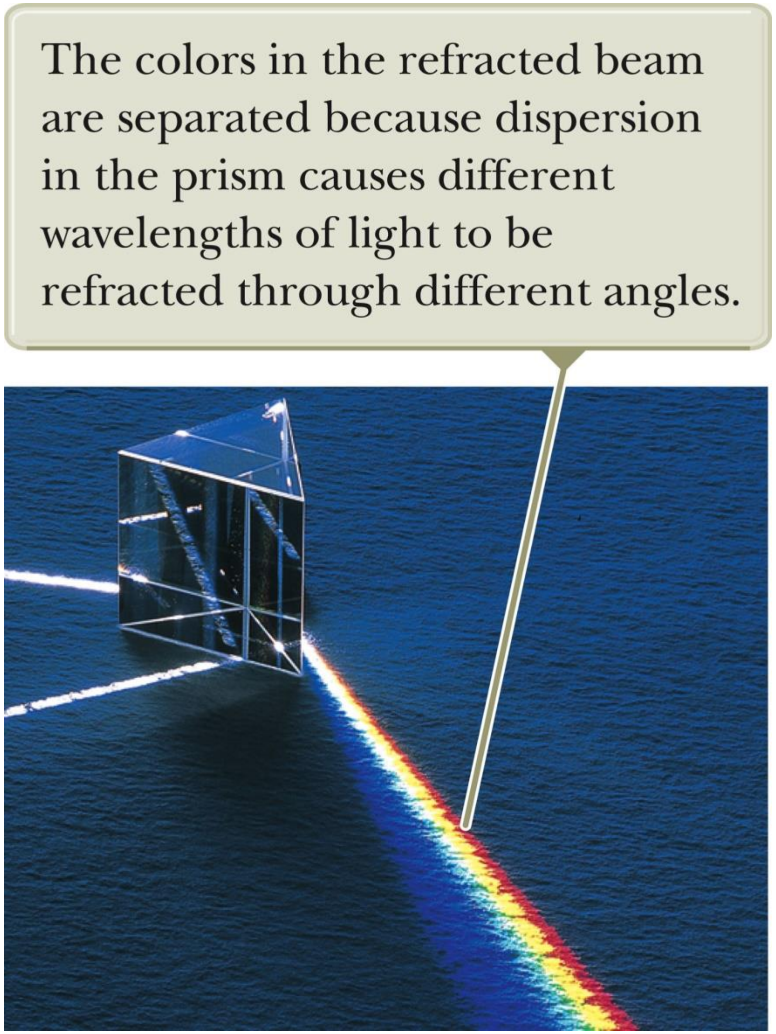
Violet light bends more than red light when passing into a refracting material.



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

A ray of light strikes a drop of water in the atmosphere.

It undergoes both reflection and refraction.

- First refraction at the front of the drop
  - Violet light will deviate the most.
  - Red light will deviate the least.

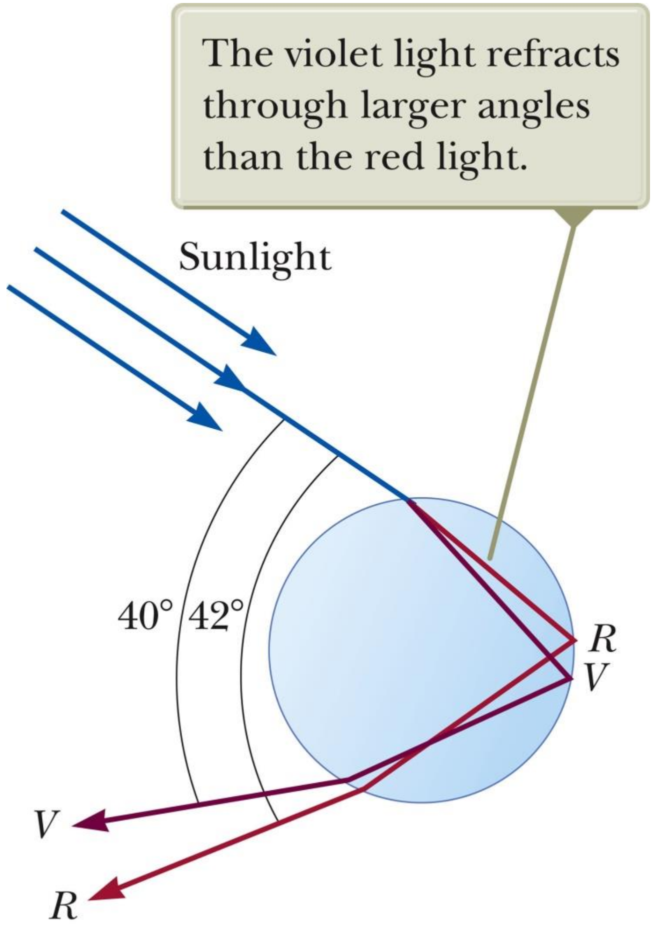
The Rainbow, cont.

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°.



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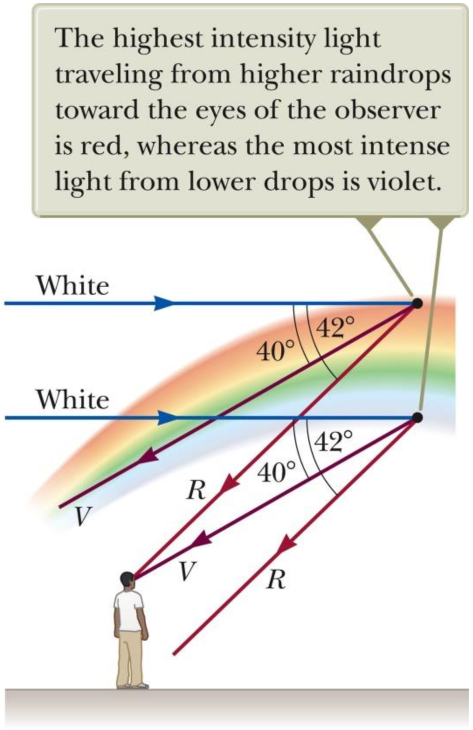
Observing the Rainbow



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.

Double Rainbow

The secondary rainbow is fainter than the primary.

The colors are reversed.

The secondary rainbow arises from light that makes two reflections from the interior surface before exiting the raindrop.

Higher-order rainbows are possible, but their intensity is low.

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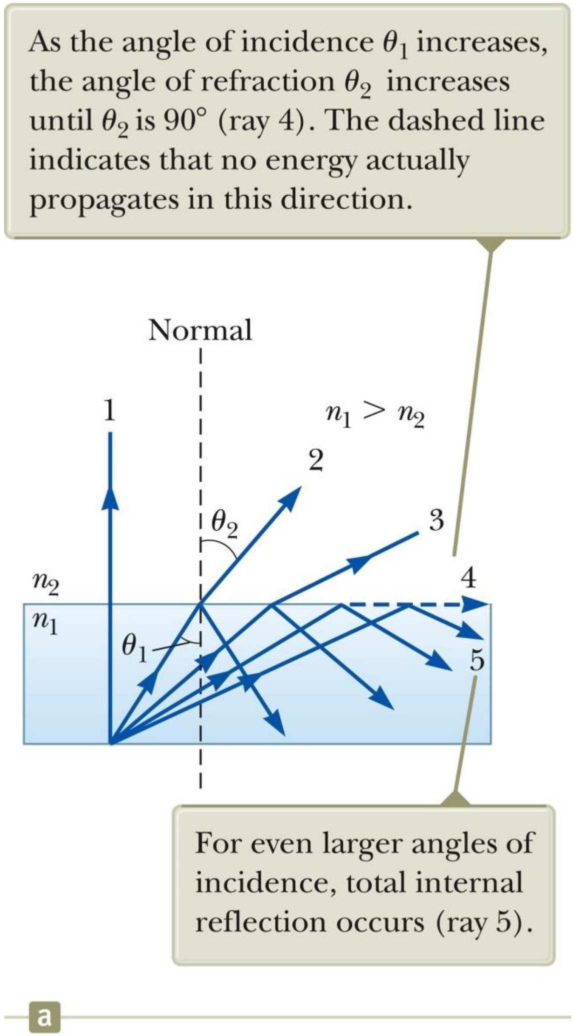
Total Internal Reflection

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 $n_1 > n_2$.

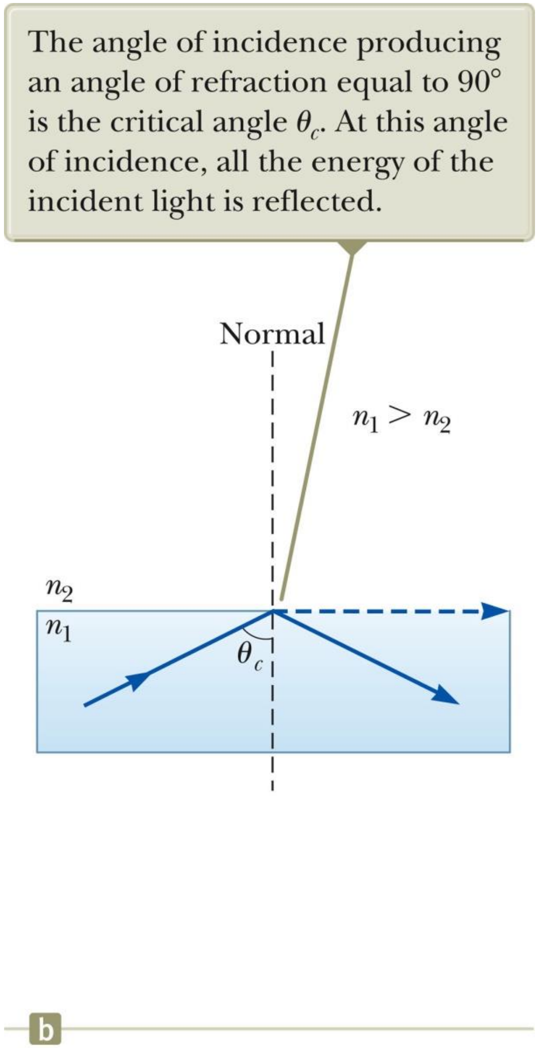


Critical Angle

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.

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



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.

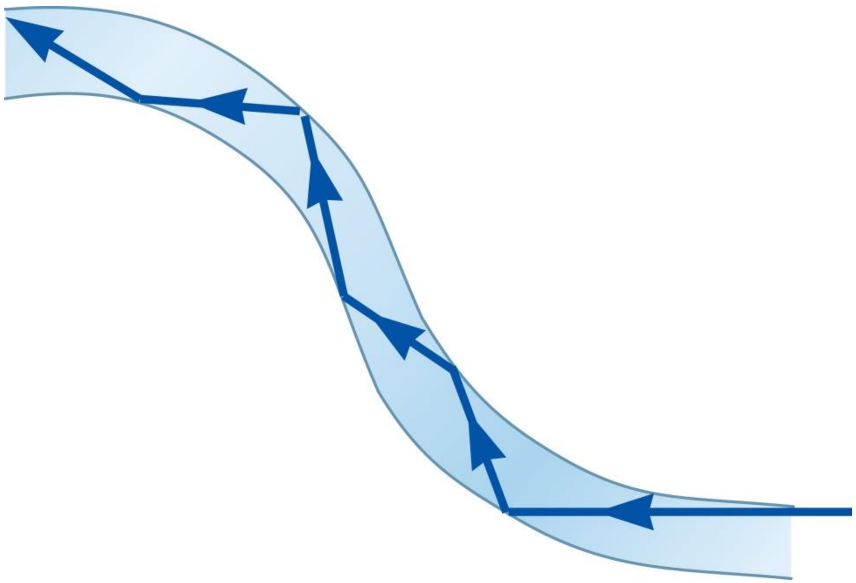
Fiber Optics

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

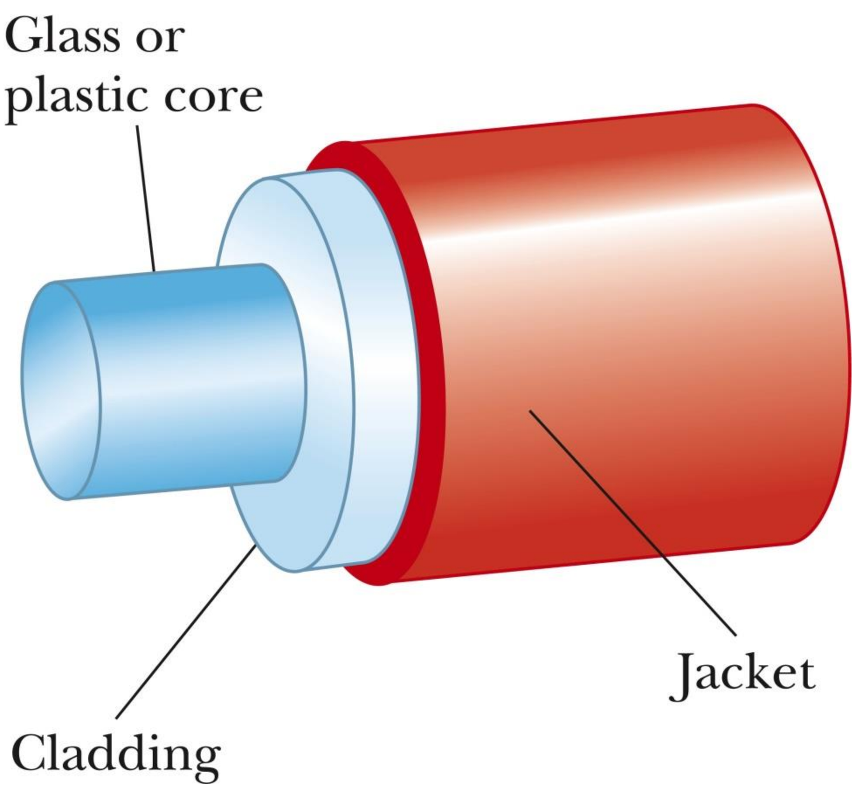


Construction of an Optical Fiber

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.

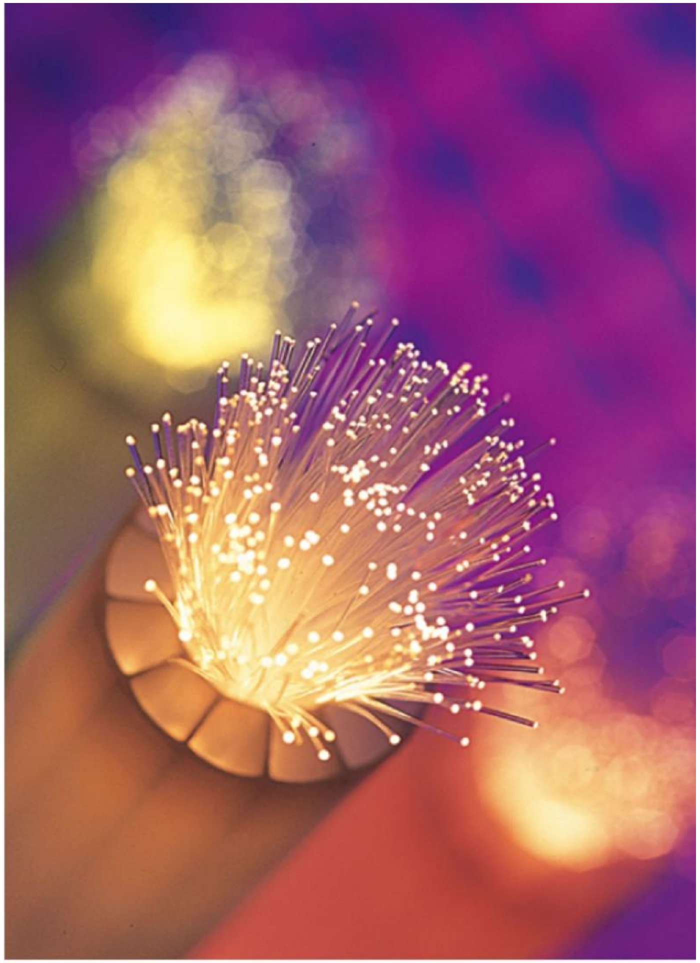
The combination is surrounded by the jacket.



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.



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