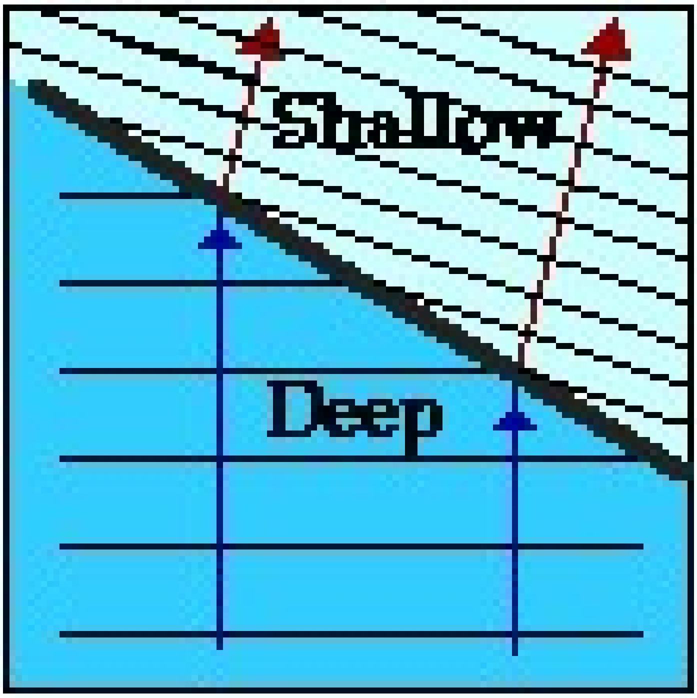
Refraction

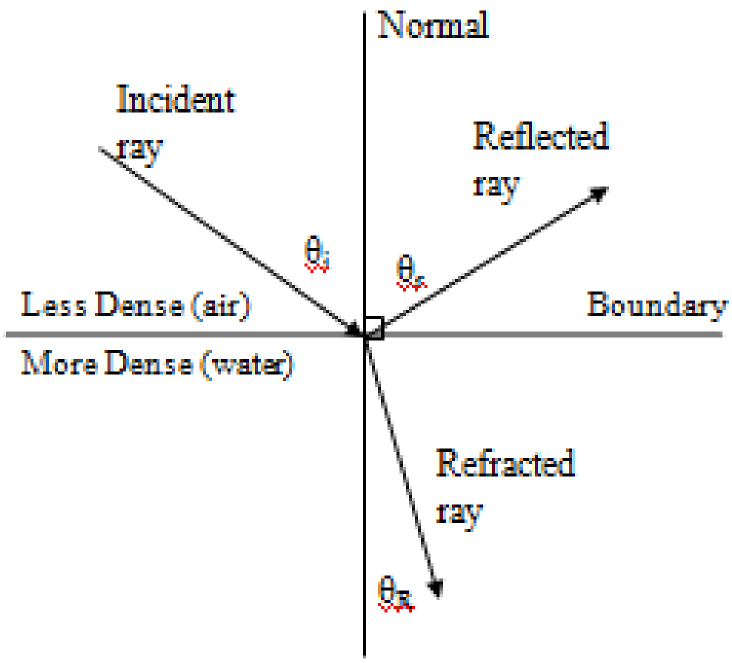
Refraction is the change of direction of a ray of light as it travels into different media. (Different media means different densities).



www.physicsclassroom.com/Class/waves/u10l3b.html

- Waves change direction as they enter shallow water.
- The same is true for light. Light changes direction as enters different media at an angle.
- How the light will bend depends on how the two media compare in density & physical structure.

- The ray diagrams below illustrate what happens to light for the two cases.

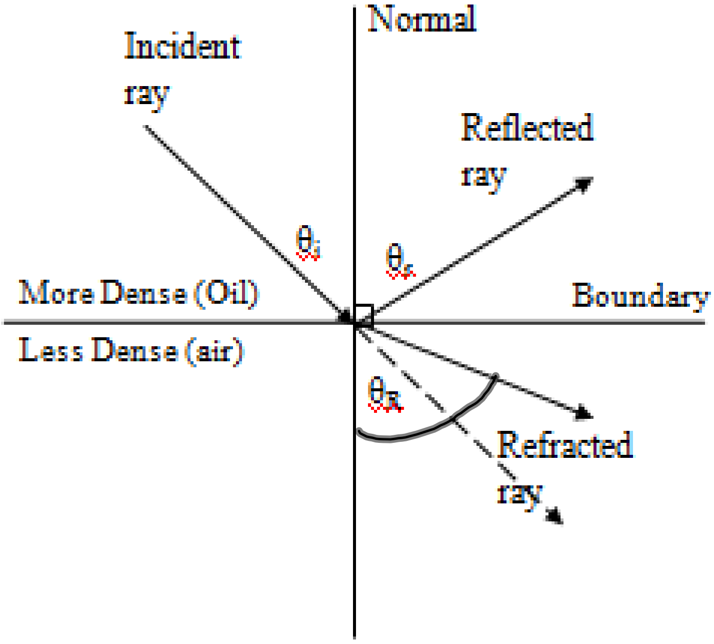


Refraction from a less dense to denser medium:

⇨ The angle of refraction, θ_R, is less than the incident angle, θ_i.

⇨ The refracted ray bends towards the normal → light slows down.

⇨ This will always be the case if light is coming from air and into anther medium.



Refraction from a more dense to less dense medium:

- ⇨ The angle of refraction, θ_R, is more than the incident angle, θ_i.
- ⇨ The refracted ray bends away from the normal → light speeds up.
- ⇨ If the angle of incidence is zero, there is no change of direction, but there is a change of speed.
- ⇨ <u>Principle of Reversibility</u>: If a light ray is reversed, it travels back along its original path.

Index of Refraction

To understand the behavior of light in different properties, we refer to the index of refraction n
It is the ratio of the speed of light in a vacuum, c, to the speed of light in a given material, v.
Mathematically,

$$n = \frac{c}{v}$$

The higher the index of refraction, the more light is slowed down when it travels from a vacuum in to a substance.

Examples

1. The speed of light in a liquid is 2.25×10^{8} m/s. What is the refractive index of the liquid?

$n = ?$

$v = 2.25 \times 10^{8}$ m/s

$c = 3.00 \times 10^{8}$ m/s

$$n = \frac{c}{v} = \frac{3.00 \times 10^{8}\ \text{m/s}}{2.25 \times 10^{8}\ \text{m/s}}$$

$$n = 1.33$$

2. Calculate the speed of light in Lucite (Plexiglas), if $n_{lucite} = 1.51$

$n = 1.51$

$c = 3.00 \times 10^8 \, m/s$

$v = ?$

$n = \frac{c}{v}$

$1.51 = \frac{3.00 \times 10^8 \, m/s}{v}$

$1.51 v = 3.00 \times 10^8 \, m/s$

$v = \frac{3.00 \times 10^8 \, m/s}{1.51}$

$v = 2.00 \times 10^8 \, m/s$

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Indices of Refraction	
Substance	Index of Refraction (*n*)
Vacuum	1.0000
Air (0°C, 101 kPa)	1.0003
Water	1.33
Ethyl alcohol	1.36
Quartz (fused)	1.46
Glycerin	1.47
Lucite or Plexiglas	1.51
Glass (crown)	1.52
Sodium chloride	1.53
Glass (crystal)	1.54
Ruby	1.54
Glass (flint)	1.65
Zircon	1.92
Diamond	2.42
Note: For yellow light, wavelength = 589 nm	

Laws of Refraction

Willebrod Snell (1591 – 1626) was able to determine the exact relationship between the angle of incidence and the angle of refraction.

#21) Fused Quartz

$d = vt$

$v_{FQ} = \frac{c}{n}$

$= \frac{3\times10^8}{1.46} = 2.05\times10^8 \, m/s$

$0.25 = (2.05\times10^8)t$

$\frac{0.25}{2.05\times10^8} = t$

$1.22\times10^{-9}s = t$

or 1.22ns

Zircon

$n = 1.92$

$v = \frac{c}{n} = \frac{3.00\times10^8}{1.92}$

$v = 1.56\times10^8 \, m/s$

$d = vt$

$0.55 = (1.56\times10^8)t$

$3.53\times10^{-9}s = t$

or 3.53ns

Total time

$= 1.22ns + 3.53ns$

$= 4.75ns$

or $4.75\times10^{-9}s$

#19)

$\lambda_B = 455\,nm \leftarrow$ vacuum

$\lambda_B = ? \leftarrow$ in ruby

$$n = \frac{c}{v} = \frac{(f_{vac})(\lambda_{vac})}{(f_{ruby})(\lambda_{ruby})}$$

$\uparrow$

1.54

$f_{vac} = f_{ruby}$

$$1.54 = \frac{\lambda_{vac}}{\lambda_{ruby}}$$

$$1.54 = \frac{455\,nm}{\lambda_{ruby}}$$

$$\lambda_{ruby} = \frac{455\,nm}{1.54}$$

$$\boxed{= 295\,nm}$$

- This enables us to predict the direction a ray of light would take in various media.

⇨ This is called <u>Snell's Law</u>:

$$\frac{\sin i}{\sin R} = \text{constant}$$

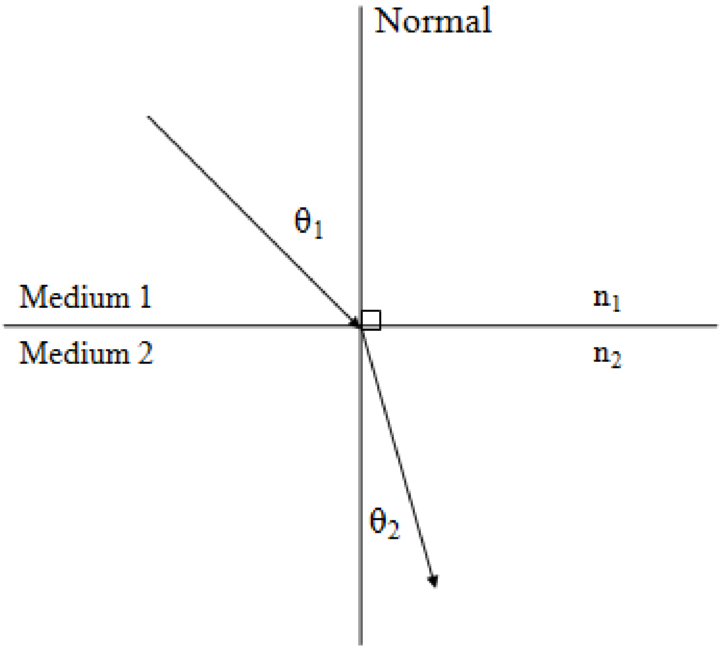
⇨ Where i = angle of incidence and R = angle of refraction.

⇨ If light is traveling from a vacuum, the constant is the index of refraction of the material.

The Laws of Refraction are:

1. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant (Snell's Law).
2. The incident ray and the refracted ray are on opposite sides of the normal at the point of incidence, and all three lie in the same plane.

Snell's Law – A General Equation



Mathematically we write:

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$$

or

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

Examples

1. Light travels from crown glass into air. The angle of refraction in air is 60°. What is the angle of incidence in glass?

$\theta_1 = ?$ ← θ_i ← incidence

$\theta_2 = 60°$ ← θ_R ← refraction

$n_1 = 1.52$

$n_2 = 1.0$

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

$(1.52)\sin\theta_1 = (1)\sin 60$

$$\sin\theta_1 = \frac{\sin 60}{1.52}$$

$\sin\theta_1 = 0.5697$

$\theta_1 = \sin^{-1}(0.5697)$

$\boxed{\theta_1 = 35^0}$

2. Light travels from crown glass into water. The angle of incidence in crown glass is 40°. What is the angle of refraction in water?

$n_1 = 1.52$

$n_2 = 1.33$

$\theta_1 = 40°$

$\theta_2 = ?$

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

$1.52 \sin 40 = 1.33 \sin\theta_2$

$0.977 = 1.33 \sin\theta_2$

$0.7346 = \sin\theta_2$

$47° = \theta_2$

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Total Internal Reflection and the Critical Angle

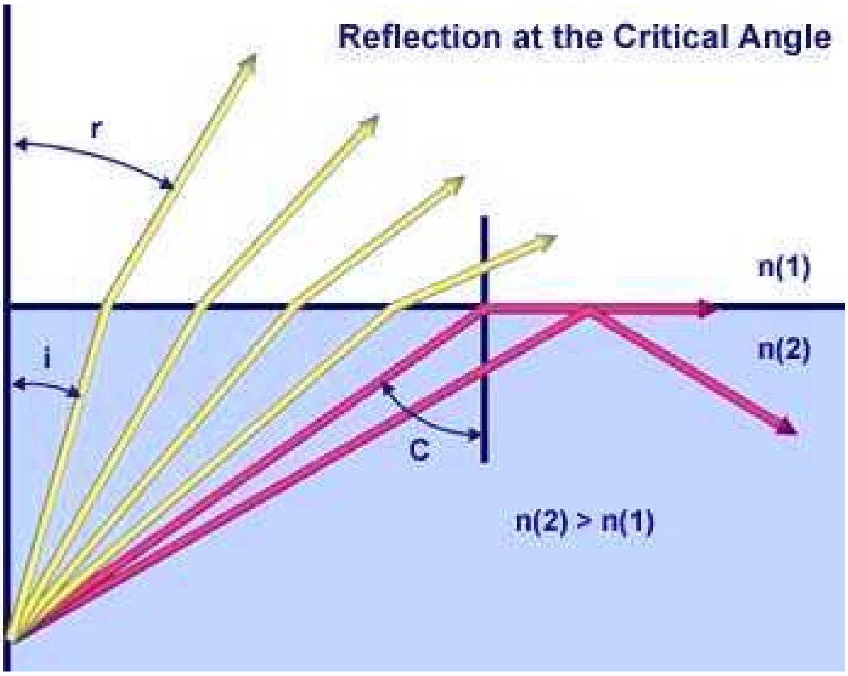
⇨ When light travels into a medium where its speed changes, some light is reflected, and some is refracted.

⇨ As the angle of incidence increases, the intensity of the reflected ray increases. The intensity of the refracted ray decreases.

⇨ Total internal reflection occurs when light travels into a faster medium and the angle of refraction is 90° or greater.

⇨ When the angle of refraction is 90°, the angle of incidence is called the critical angle, angle *C*.

⇨ Angles of incidence greater than the critical angle result in total internal reflection.



Virginia University website: galileo.phys.virginia.edu/. ../introduction.htm

Example

1. The critical angle for light traveling from crown glass into air can be found with Snell's Law.

$$n_i \sin\theta_i = n_R \sin\theta_R$$

$n_i = 1.52$

$n_R = 1.0$

$\theta_i = \theta_c = ?$

$\theta_R = 90^\circ$

$$1.52 \sin\theta_c = 1.0 \sin 90^\circ$$

$$1.52 \sin\theta_c = 1.0$$

$$\sin\theta_c = 0.6579$$

$$\theta_c = 41^\circ$$

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