Refraction and Snell's Law

by

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P4.9 Nature of Light

Light interacts with matter by reflection, absorption, or transmission.

P4.9A Identify the principle involved when you see a transparent object (e.g., straw, a piece of glass) in a clear liquid.

P4.9B Explain how various materials reflect, absorb, or transmit light in different ways.

P4.9C Explain why the image of the Sun appears reddish at sunrise and sunset.

P4.8e Given an angle of incidence and indices of refraction of two materials, calculate the path of a light ray incident on the boundary (Snell's Law).

P4.8f Explain how Snell's Law is used to design lenses (e.g., eye glasses, microscopes, telescopes, binoculars).

Items;

1- Light, Refraction

2- Index of Refraction

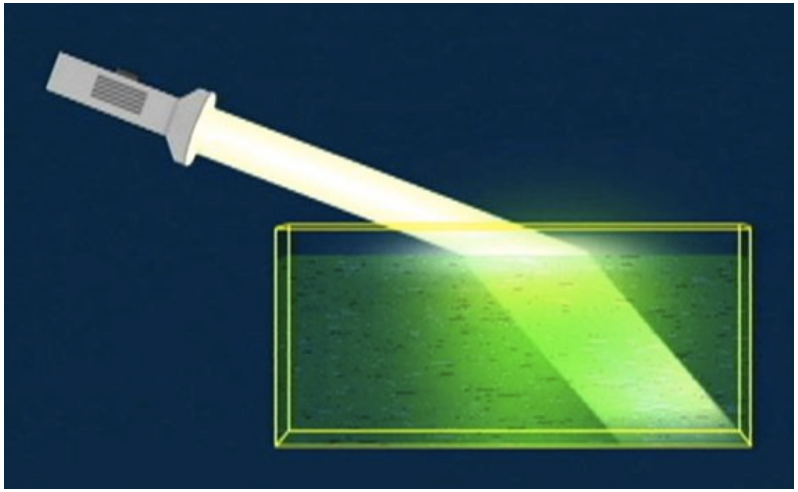
3- Snell’s Law of Refraction

4- Apparent Depth

LIGHT, REFRACTION

Light travels through a vacuum at a speed $c = 3.00 \times 10^8$ m/s.

Light travels through materials at a speed less than its speed in a vacuum. Therefore, light changes its direction as it passes, at an angle, from one medium to another. This is called refraction.

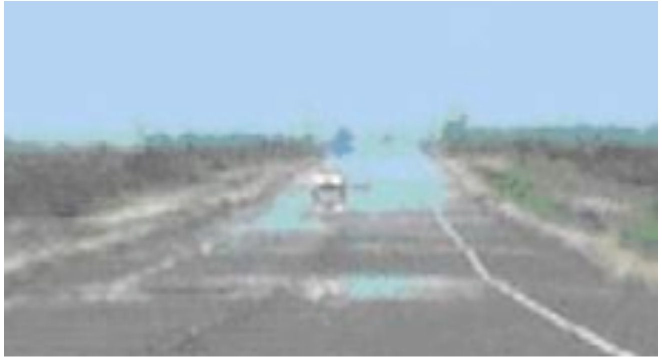


Example1: *Refraction or Change in Direction Applications;*

a) A straight stick appears bent when partially immersed in water.

b) The sun appears oval rather than round when it is about to set.

c) The pavement shimmers on a hot summer's day.



INDEX OF REFRACTION

The index of refraction (*n*) of a material is the ratio of the speed of light in a vacuum (*c*) to the speed of light in the material (*v*):

Index of Refraction Formula

$$n = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in the material}} = \frac{c}{v}$$

or

$$v = c / n$$

or

$$c = n \times v$$

Index of Refraction of Various Substances

Substance	Index of Refraction, n
Solids at 20 °C	
Diamond	2.419
Glass, crown	1.523
Ice (0 °C)	1.309
Sodium chloride	1.544
Quartz	
Crystalline	1.544
Fused	1.458
Liquids at 20 °C	
Benzene	1.501
Carbon disulfide	1.632
Carbon tetrachloride	1.461
Ethyl alcohol	1.362
Water	1.333
Gases at 0 °C, 1 atm	
Air	1.000 293
Carbon dioxide	1.000 45
Oxygen, O_2	1.000 271
Hydrogen, H_2	1.000 139

[a] Measured with light whose wavelength in a vacuum is 589 nm.

Example 2: *Refractive Index of a Liquid;*

The speed of light in a liquid is 2.25×10^8 m/s. What is the refractive index of the liquid? The speed of light in a vacuum is: $c = 3.00 \times 10^8$ m/s.

Data Table		
c	v	n
3.00×10^8	2.25×10^8	?

$$n = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in the material}} = \frac{c}{v}$$

$$n = c / v = 3.00 \times 10^8 / 2.25 \times 10^8 = 1.33$$

Using the table above (Index of Refraction of Various Substances) the liquid is probably water.

Example 3: *Speed of Light and Medium;*

Using the table above (Index of Refraction of Various Substances) calculate the speed of light in benzene.

The speed of light in a vacuum is: $c = 3.00 \times 10^8$ m/s.

According to the table, the index of refraction of benzene (n) is 1.50

Data Table		
c	v	n
3.00×10^8	?	1.50

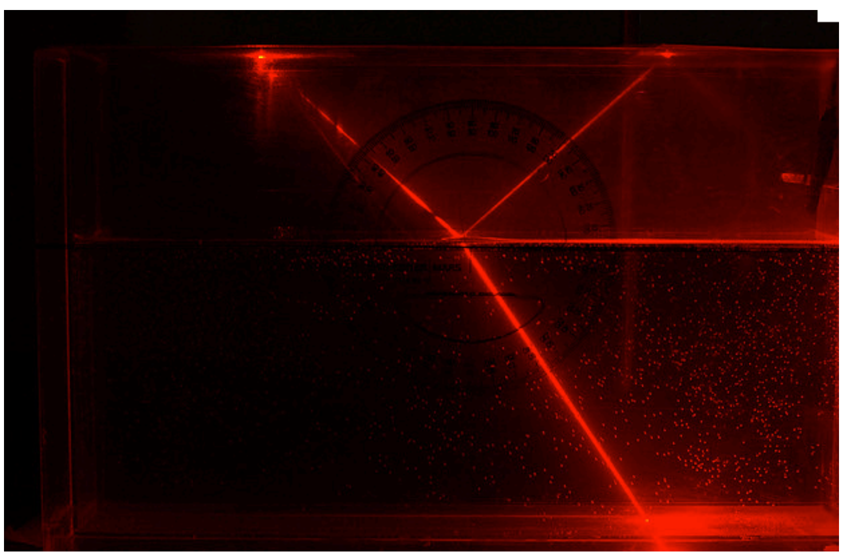
$$n = \frac{\text{Speed of light in vacuum}}{\text{Speed of light in the material}} = \frac{c}{v}$$

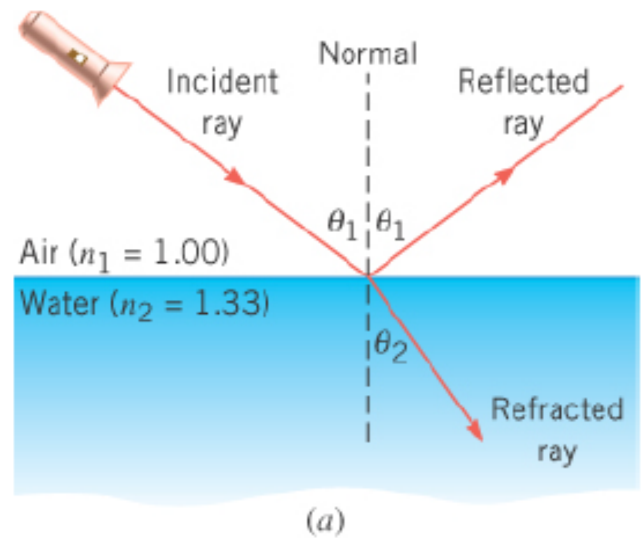
$$v = c / n = 3.00 \times 10^8 / 1.50 = 2.0 \times 10^8 \text{ m/s}$$

Snell's Law and the Refraction of Light

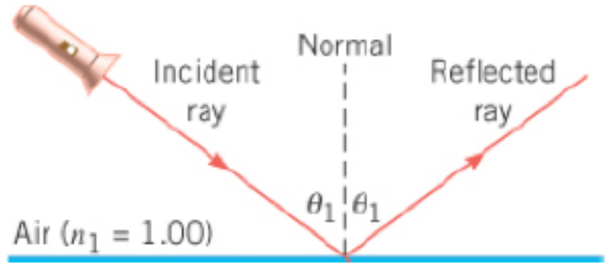
When light strikes, at an angle, an interface between two transparent materials, it breaks up into two pieces - one reflected and one refracted (transmitted).

The diagram, shown below, illustrates this phenomena when light passes between air the water and shows both partial reflection and refraction.



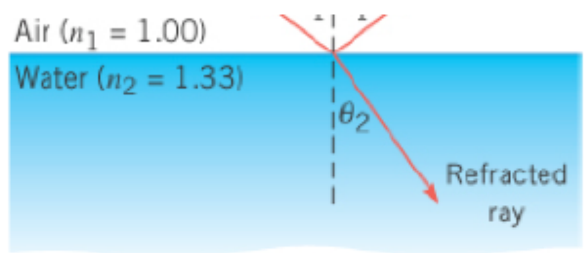


Partial Reflection: Part of the light is reflected. The angle of incidence and the angle of reflection are equal (θ_1).



The angle of incidence is the angle between the incident ray and the normal at the point of incidence. The angle of reflection is the angle between the reflected ray and the normal.

Partial Refraction: The remainder of light is transmitted across the interface and change direction. The ray that enter the second material is said to be refracted. The angle of refraction (θ_2) is the angle between the refracted ray and the normal.

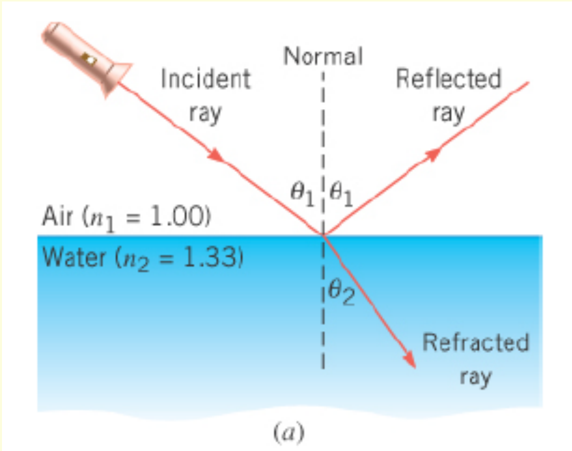


(a)

SNELL'S LAW OF REFRACTION

Willebrod Snell (1591-1626), a Dutch Mathematician, determined the exact relationship between the angle of incidence and the angle of refraction.

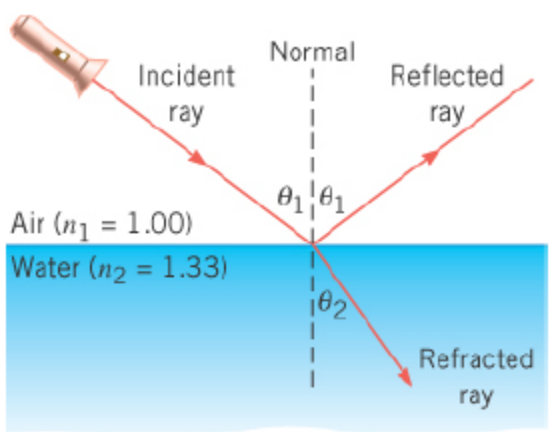
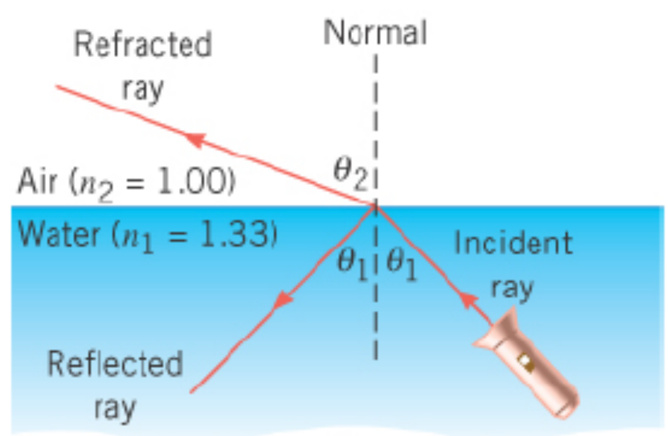
When light travels from a material with one index of refraction (n_1) to a material with a different index of refraction (n_2), the angle of incidence (θ_1) is related to the angle of refraction (θ_2) by:

Snell's Law of Refraction	
$n_1 \sin\theta_1 = n_2 \sin\theta_2$	

The incident ray, the reflected ray, and the normal to the surface all lie in the same plane.

a) When light passes from an incident medium of smaller refractive index (air) into a medium (water) of larger refractive index ($n_1 < n_2$) the refracted ray bends closer to the normal ($\theta_2 < \theta_1$).   Example is figure (a) below.

b) When light passes from an incident medium of larger refractive index (water) into a medium (air) of smaller refractive index ($n_1 > n_2$) the refracted ray bends away from the normal ($\theta_2 > \theta_1$). Example is figure (b) below.

$n_1 < n_2$	$n_1 > n_2$
 (a)	 (b)

Subscript 1 is used for the incident medium, and subscript 2 is normally used for the refracting medium.

Example 4: Refraction Through Air/Water Surface

A light ray strikes an air/water surface at an angle of 46 degrees with respect to the normal. Find the angle of refraction when the direction of the ray is:

(a) from air to water and

(b) from water to air.

Data Table			
n_{air}	n_{water}	θ_1	θ_2
1.00	1.33	46^o	?

According to Snell's law of refraction:

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

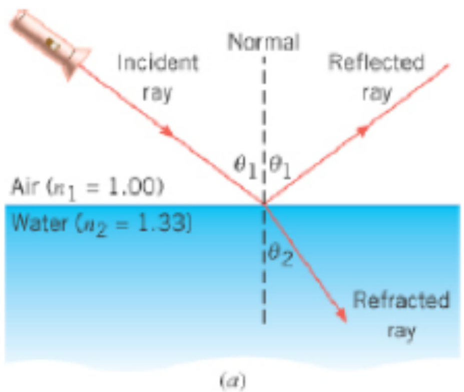
So

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

a) medium (1) is air (n_1 = 1.00). It has the angle of incidence (θ_1).

medium (2) is water (n_2 = 1.33). It has the angle of refraction (θ_2)

Data Table			
$n_{1\ \text{or air}}$	$n_{2\ \text{or water}}$	θ_1	θ_2
1.00	1.33	46°	?



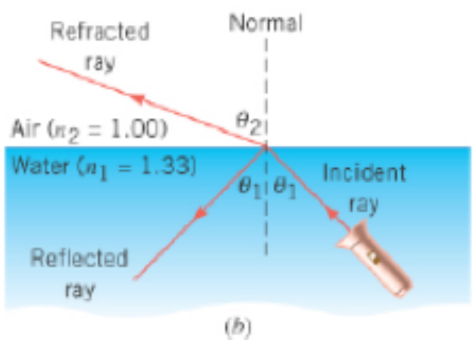
(a) $$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{(1.00)\sin 46^\circ}{1.33} = 0.54$$

$$\theta_2 = 33^\circ$$

$\theta_2 = \sin^{-1}(0.54) = 33^\circ$

b) medium (1) is water (n_1 = 1.33) . It has the angle of incidence (θ_1).
medium (2) is air (n_2 = 1.00). It has the angle of refraction (θ_2)

Data Table			
$n_{1 \text{ or water}}$	$n_{2 \text{ or air}}$	θ_1	θ_2
1.33	1.00	46°	?

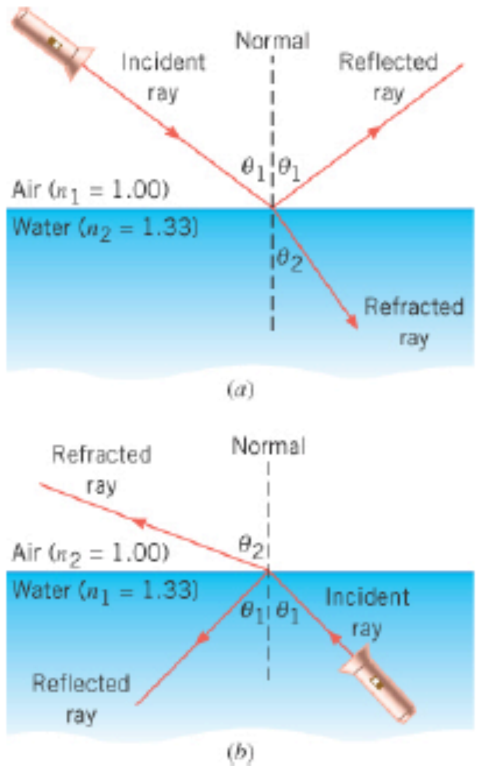


(b) $$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{(1.33)\sin 46^\circ}{1.00} = 0.96$$

$$\theta_2 = 74^\circ$$

$\theta_2 = \sin^{-1}(0.96) = 74^\circ$

Summary;



(a) $$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{(1.00)\sin 46^\circ}{1.33} = 0.54$$

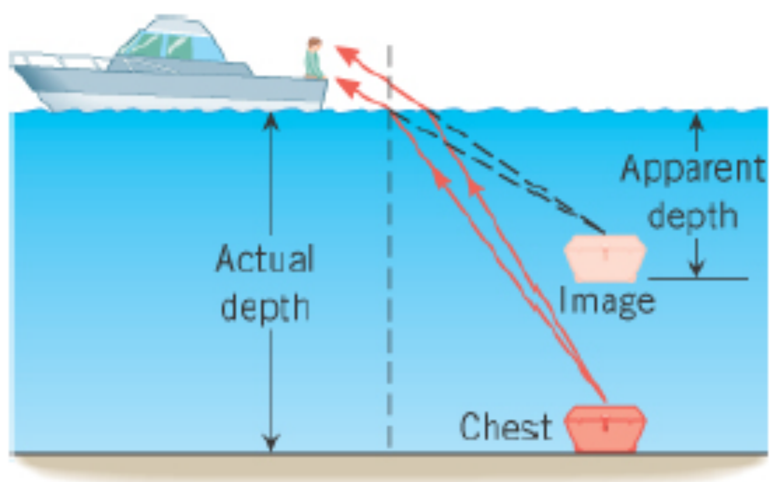
$$\theta_2 = 33^\circ$$

(b) $$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2} = \frac{(1.33)\sin 46^\circ}{1.00} = 0.96$$

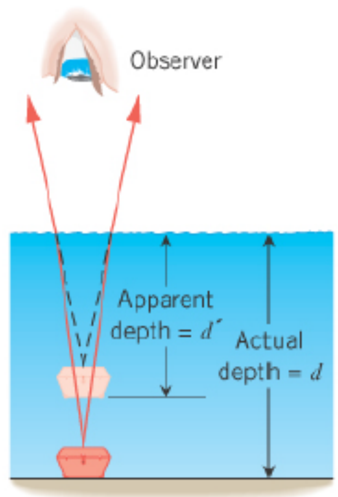
$$\theta_2 = 74^\circ$$

APPARENT DEPTH

A sunken chest is viewed from a boat. The light from the chest is refracted away from the normal when it enters the air and then travels to the observer.
When the rays are extended back into the water, they indicate that an observer sees a virtual image of the chest.
The apparent depth of the image is less than the actual depth.



Similarly, looking directly above the object at an actual depth *d*, the object appears closer at an apparent depth of *d'*.



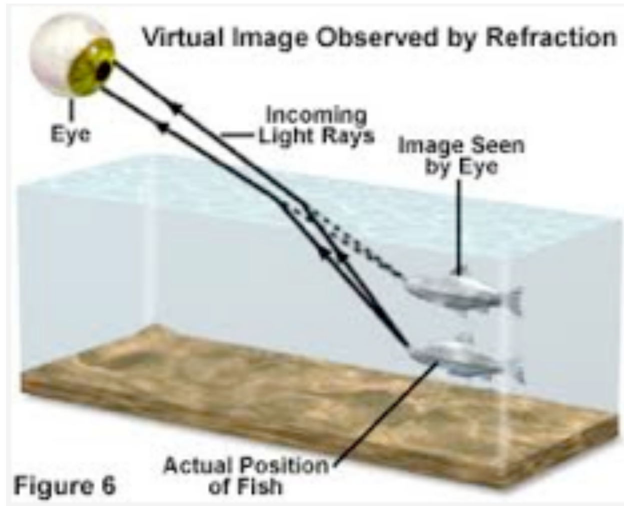
The apparent depth *d'* observed directly above object can be calculated:

$$d' = d\left(\frac{n_2}{n_1}\right)$$

n_1 refractive index of medium 1, or medium of object,

n_2 refractive index of medium 2, or medium of observer,

Example 5: *Virtual Image of a Fish Observed by Refraction.*



Example 6*: Depth of a Stream*

A stream may appear to be much shallower than you know it to be.

References:

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2) Cutnell, J. D. & Johnson, K. W. (1998). *Cutnell & Johnson Physics, Fourth Edition*. New York: John Wiley & Sons, Inc.

The edition was dedicated to the memory of Stella Kupferberg, Director of the Photo Department: "We miss you, Stella, and shall always remember that a well-chosen photograph should speak for itself, without the need for a lengthy explanation"

3) Martindale, D. G. & Heath, R. W. & Konrad, W. W. & Macnaughton, R. R. & Carle, M. A. (1992). *Heath Physics.* Lexington: D.C. Heath and Company

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