The Refraction of Light

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Light, (electromagnetic wave), travels in a straight line and at constant speed as long as the medium it is travelling in is the same.

A medium (plural: media) is a material that is being used or is undergoing a process.

However, when light travels from one medium to another, for example from air to water, the light rays travel at different speed in each medium causing the light rays to bend or refract; i.e. both the direction and the speed of the light rays change.

Refraction is a property of light in which the speed of light and its direction of travel change resulting from a change in speed of the electromagnetic wave. (The fact that light rays undergo refraction is evidence to support the idea that light is a wave motion.)

Different media slow down light by different amounts. The more that light slows down, the more the light is refracted.

[**Analogy**: consider a car travels at an angle from the road onto mud or snow, as the right front wheel will hit the mud/snow, the car will slow down. The left front wheel of the car does not slow down because it is still on the road. This results in the car pivoting about the slower right front wheel. Hence, the direction of the car changes as it moves from the road onto the mud/snow.
The speed of light is different in different media, thus resulting in the light rays being refracted. Refraction is due to changes in the speed of light.]

Refraction is the bending or change in direction of light as it passes from one medium into another.

The Speed of Light, c

[FYI: the symbol 'c' for speed of light comes from the Latin word 'celeritas' meaning 'velocity'.]

Light has a definite speed. The speed of light depends on the medium that it is passing through.

A ray of light is electromagnetic radiation, which is transmitted in waves. The particles in a medium decrease the speed of the waves, resulting in light travelling at a slower speed. There is also a slight variation in speed that depends on colour.

The speed of light is different for each medium, but is always less than the speed of light in a vacuum. Light travels at a speed of 3.00×10^8 m/s in a vacuum.

Light travels at a speed of 2.26×10^8 m/s in water, (i.e. slower than in air, measured by Thomas Young in ~1830, his experiment further clinched the wave theory of light); at a speed of 1.76×10^8 m/s in acrylic, and at a speed of 1.24×10^8 m/s in diamond.

The change in the speed of light at the boundary of a substance causes refraction.

The speed of light in a medium is a distinctive optical property of that medium.

Note: the speed of light in air is slightly less than the speed in a vacuum.
The difference, however, is so small that it is not significant, (the number of significant digits used in our calculations).
Therefore, the value used for the speed of light in air, 3.00×10^8 m/s, used will be the same as the speed of light in a vacuum.

The Index of Refraction for Light

Light slows down as it passes from a vacuum into any other medium.

The amount by which a transparent medium decreases the speed of light is indicated by a number called the **index of refraction, n**, also referred t as the **refractive indices**.

Index of refraction, n, is the ratio of the speed of light in a vacuum to the speed of light in a given medium.

The refractive index of a medium, n, is determined by comparing the speed of light in the medium, v, with the speed of light in a vacuum, c, i.e. the refractive index, n, is a ratio of the speed of light in a vacuum, c, to its speed in a medium, v.

$$\text{Index of refraction of a material, } n = \frac{\text{speed of light in vacuum, } c}{\text{speed of light in medium, } v}$$

$$n = \frac{c}{v} \qquad \text{[See later notes: } n = \frac{\sin \theta i}{\sin \theta_R} \text{]}$$

The ratio of the two speeds has no units because it is a ratio of identical physical quantities.
Light travels the fastest in a vacuum.
The refractive index of the speed of light in a vacuum is assigned a value of 1.00.
A value of 1.00 can also be used for air.

The larger the refractive index, n, the more the medium decreases the speed of light.

Diamond	Pyrex glass
n = 2.42	n = 1.47
more refractive	Less
bends light more, light travels more slowly	less, less

Notes on reporting Indices of Refraction:
1. That the value for water, glass, diamond and other media all slow down light, they have higher values than air.

2. The value for the index of refraction is always greater than 1, because the speed of light is always higher in a vacuum than in a medium. (*As the speed of light decreases due to the medium, the index of refraction increases*.)

3. When index of refraction is recorded for a gas, both temperature and pressure are reported since gases are affected by changes in temperature and pressure. Since liquids and solids are affected by temperature, so in tables of indices of refraction the temperature is reported.
The Table below show the refractive indices for some common materials

Index of Refraction for some Media (Gases at 0^{O}C and 101.3 kPa, Liquids and Solids at 20 ^{O}C)

Media	**Index of Refraction, n**
vacuum	1.0000
Air	1.0003
water	1.33
Alcohol (ethanol)	1.36
Pyrex glass	1.47
Ruby	1.54
Sapphire	1.77
Cubic zirconia	2.16
Diamond	2.42

Applications

The index of refraction can be used to identify a substance. For example that a ring may be made of diamond or zirconia. Upon measuring the speed of light through the ring and if calculations indicate the index of refraction to be 2.16, then the ring is composed of zirconia !

Calculations

1. The speed of light in a sample of glass is 1.91×10^8 m/s. The speed of light in a vacuum is 3.00×10^8 m/s. What is the refractive index of this glass? (Answer: 1.57)

2. What is the speed of light through sapphire given that sapphire has a refractive index of 1.77 ?

3. The speed of light in quart is 2.1×10^8 m/s. What is the index of refraction of quartz ?

4. The speed of light in sodium chloride (salt, NaCl) is 1.96×10^8 m/s. The speed of light in a vacuum is 3.00×10^8 m/s. Calculate the index of refraction for sodium chloride.

5. What is the speed of light in olive oil given that the index of refraction for olive oil is 1.48.

6. The speed of light in vinegar is 2.30×10^8 m/s. Determine the index of refraction for vinegar.

7. The speed of light in an unknown substance is 2.20×10^8 m/s.
a. Calculate the index of refraction for this substance.
b. Use the above Table of Indices of Refraction to identify the unknown substance.

8. Why is the index of refraction a unique property of a medium?

9. What is meant by the term' index of refraction'? Why is it a dimensionless quantity?

10. An 80 % sugar solution has an index of refraction of 1.49. Calculate the speed of light in this solution.

Snell's Law and The Laws of Refraction

When a light ray is incident on the boundary between two materials of different refractive index, then the incident ray is reflected and *in addition* there is now a refracted ray in the second material. [FYI: the word refract comes from the Latin word *refringere*, which means to break up.]

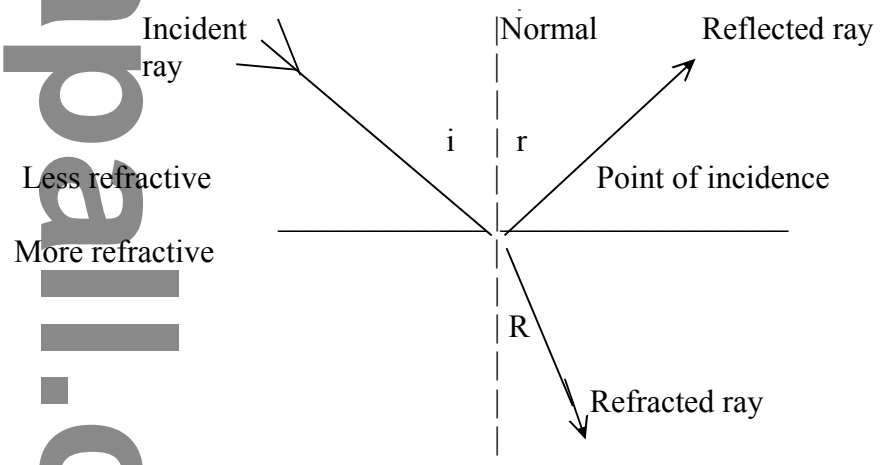
When light strikes the surface of a material at an angle, then the light ray that enters the surface of the second material will slow down — this changes the direction of the light ray (an electromagnetic wave) at the surface as it enters.

Refraction is the bending of light as it passes at an angle from a material of one refractive index to a material of a different refractive index.

The incident ray is divided into two rays — one that reflects and one that refracts.

The **incident ray** is the ray of light approaching the boundary between the two media, while the **refracted ray** is the ray of light leaving the boundary. The incident ray, the reflected ray, and the refracted ray are all shown in the diagram below.
The **normal** is the line perpendicular to the boundary at the point of incidence.

Diagram: Refraction of light



The **angle of incidence, i**, is the angle between the incident ray and the normal.

The **angle of refraction, R,** is the angle between the refracted ray and the normal.

When light slows down upon entering a medium at some angle from the normal, it bends towards the normal.
[If you think of a line of people running along a beach, holding hands, and then into some water, the line will change direction slightly because the people running in the water are moving more slowly.]
The path of light shown above is reversible—when light travels from a slow medium to a fast medium, the path bends away from the normal.

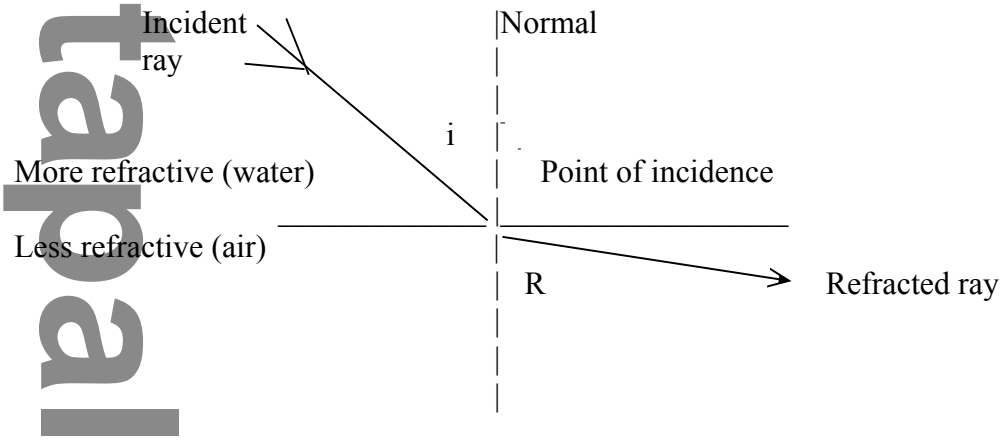
Rules of Refraction

1.The incident ray, the refracted ray, and the normal all lie in the same plane. The incident ray and the refracted ray are on the opposite sides of the line that separate the two media.

2. Light bends toward the normal when the speed of light in the second medium is less, (with a higher refractive index) than the speed of light in the first medium, (with a low refractive index). (Example from air to glass)

However, light bends away from the normal when the speed of light in the second medium is greater, i.e. when light travels from a denser, higher refractive index medium into a less optically dense, lower refractive index medium . (Example from glass to air)

Diagram: Light ray travelling from a medium in which its speed is slower (higher refractive index) to a medium in which its speed is faster, (lower refractive index), the refracted ray is bent away from the normal.



Note that reflection always occurs. Light can undergo partial reflection and refraction at the same time at a surface.
However, when discussing refraction, the reflected ray will be omitted in order to focus on the angle of refraction and refracted ray. But the reflected rays are important for later notes.

Terminology

N = normal
θ = 'theta', a variable used frequently for angles
θ_i = angle of incidence
θ_R = angle of refraction
n = refractive index for a medium, indicates how much the incident ray was 'bent' in becoming the refracted ray**.**

Snell's Law: The Relationship between Angle of Incidence, i, and the Angle of Refraction, R

Willebrord Snell (1591 –1626), a Dutch astronomer, is credited with discovering the relationship between the angle of incidence, θi, and the angle of refraction, θ_R

If n_1 and n_2 are the indices of refraction of the two media and the angle of incidence and the angle of refraction are θ_i and θ_R, (See diagram below), then the formula for Snell's Law is:

Snell discovered that for any two media: $\frac{\sin \theta_i}{\sin \theta_R} = \text{a constant} = n_2$

This equation is stated as Snell's Law: *the ratio of the sine of the angle of incidence to the sine of the angle of refraction in a medium is a constant for a given medium and colour of light.*
The *constant is a property of medium 2 alone, the refractive index of medium 2*.

Thus, Snell's law is usually written as : $\frac{\sin \theta_i}{\sin \theta_R} = n$

where θ_i = angle of incidence, θ_R = angle of refraction

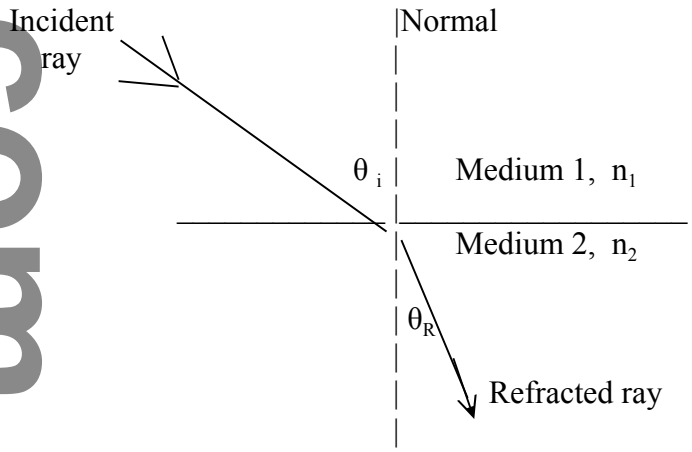
Snell's Law is a formula that uses values for the index of refraction to calculate the new angle that a ray will take as a beam of light strikes the interface between two media.

A general equation for light travelling directly from medium 1 with an index of refraction n_1, to medium 2 with an index of refraction n_2 , may be written as:

$$n_1 \sin \theta_i = n_2 \sin \theta_R$$

This equation applies no matter which way the light is travelling between the two media.

Diagram: Relationship of indices of refraction with the angle of incidence and the angle of refraction



[Note: it is also true that $n_1 v_1 = n_2 v_2$ where v is the speed of light in the medium.]

Assignment: Practice Calculations

1. A ray of sodium yellow light travels from air to diamond at an angle of incidence of 35^0. Calculate the angle of refraction, the refractive index for diamond, n = 2.42

Answer: $\frac{\sin \theta_i}{\sin \theta_R} = n$ $\therefore \sin \theta_R = \frac{\sin \theta_i}{n} = \frac{\sin 35^0}{2.42} = 0.237$ $\therefore \theta_R = 14^0$

2. When light passes from air into water at an angle of 60^0 from the normal, what is the angle of refraction?

Answer:
Given index of refraction of air = $n_1 = 1.00$
Given index of refraction of water = $n_2 = 1.33$
Angle of incidence = $\theta_i = 60^0$
Hence, angle of refraction, $\theta_R = 40.6^0 = 41^0$

3. A cubic zirconia is placed in water. A laser beam is passed from the water through the zirconia. The angle of incidence is 50^0 and the angle of refraction is 27^0. What is the index of refraction of cubic zirconia ? (Given index of refraction of water = $n_1 = 1.33$)

Answer:
index of refraction of water = $n_1 = 1.33$
Angle of incidence = $\theta_i = 50^0$
Angle of refraction = $\theta_R = 27^0$
Hence, index of refraction of cubic zirconia = $n_2 = n_1 \sin \theta_i \div \sin \theta_R = 2.2$

4. A ray of sodium yellow light travels from air to flint glass at an angle of incidence of 30^0 . Calculate the angle of refraction, the index of refraction for flint glass = 1.58 [18^0]

5. Light passes from air into diamond (n = 2.42). What angle of incidence would be necessary in order to have an angle of refraction of 20°? [55.9°]

6. Light passes from water (n = 1.33) into air. The angle of incidence in water is 30.0°. What is the angle of refraction in air? [41.7°]

7. Light passes from air into carbon disulfide. The angle of incidence is 40.0° and the angle of refraction is 23.6°. Calculate the index of refraction of carbon disulfide. [1.61]

8. Light travels from ruby into water. The angle of incidence in the ruby is 35^0. What is the angle of refraction in the water. (Index of refraction for ruby = 1.33) [42^0]

9. A ray of light leaves a clear, colourless solid and enters air. It approaches the solid – air interface with an angle of incidence of 33.5^0 , and leaves the interface with an angle of refraction of 58.5^0 . What is the index of refraction of this solid, and what could the solid be? [1.54, ruby]

10. A ray of light in a liquid approaches the air – liquid interface with an angle of incidence of 23.0^0. When the ray enters the air, it is *deviated* by 8.4^0 . What is the index of refraction of this liquid, and what is it? [1.33, water]

Assignment: Review

1. Clearly explain what is meant by the term 'refraction'.

2. (a) Explain why refraction takes place.
   (b) What conditions must be present for refraction to take place?

3. What property of light changes form one medium to another?

4. Explain why light bends when it enters the water. Include a ray diagram with your explanation.

5. The speed of light in a solid is 1.24×10^8 m/s. Calculate the index of refraction for the solid.

6. The index of refraction glycerol is 1.47, calculate the speed of light in glycerol.

7. Why must a table in indices of refraction of gases include the temperature and pressure of the gases?

8. When light passes from air into water at an angle of 30^0 from the normal, what is the angle of refraction? (Given index of refraction of air = 1.00, index of refraction of water = 1.33)

9. The refractive index of the lens in a human eye is 1.41. If a ray of light goes from the air into the lens at an angle of 55.0^0, what is the angle of refraction?

10. A block of amber is placed in water and a laser beam travels from the water through the amber. The angle of incidence is 35^0 while the angle of refraction is 24^0. What is the index of refraction of amber ?

11. A ray of yellow light travels from air to substance X at an angle of incidence of 25^0. The angle of refraction is 18^0. What is the speed of light in substance X ? [2.2×10^8 m/s]

12. Calculate the index of refraction of a material id the angle of incidence is 60^0 and the angle of refraction is 50^0. [1.1]

13. Which way will light bend id it is travelling:
a. Faster in a medium ?
b. Slower in a medium?

14. Define 'index of refraction'.

15. What refracts light more, a sapphire or a diamond ? (n(sapphire) = 1.77, n (diamond)= 2.42)

16. What direction does light bend when it travels from a denser medium to a less dense medium?