Topic 1: Light Properties - Refraction

Learning Outcomes:

i. Apply the following relationships to determine the unknown variables: $s_i s_0 = f^2$ or $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ (3)

ii. Predict the nature of the images of an object by curved mirrors either by using ray diagrams or by using the following relationships: $s_i s_0 = f^2$ or $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ (4)

iii. Define Refraction. (1)

iv. State the law of refraction. (1)

v. Apply Snell's Law: $\boldsymbol{n_1}$ **sin** $\boldsymbol{\theta_1}$ **=:** $\boldsymbol{n_2}$ **sin** $\boldsymbol{\theta_2}$ (2)

vi. Plot a graph of **sin** $\boldsymbol{\theta_1}$ against **sin** $\boldsymbol{\theta_2}$ (3)

vii. Interpret the gradient of the sin θ_1 and sin θ_2 (1)

viii. Calculate:
  a. absolute refractive index.
  b. relative refractive index.

ix. Solve problems involving absolute refractive index and relative refractive index.

x. Define the following as they relate to refraction:
  a. Critical angle
  b. Total internal reflection

xi. Calculate the critical angle of a material

xii. Predict the occurrence of total internal reflection.

xiii. State the use(application) of total internal reflection.

xiv. Construct ray diagrams to determine the position/nature of an images of an object formed by single converging or diverging lenses.

xv. Perform an experiment to investigates the characteristics of a convex lenses.

xvi. Apply one of the following relationships to determine the position of images formed by single converging or diverging lenses: $s_i s_0 = f^2$ or $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

xvii. Distinguish between real and virtual images formed by converging lenses.

xviii. Calculate magnification of images.

xix. Find the relationship between incident angle and the angle of deviation.

xx. Perform an experiment to find the refractive index of different medium.

xxi. Investigate the properties of converging and diverging lenses on a beam parallel rays.

Newton's Formula is an alternative formula used to determine an image's position:

$$S_i S_0 = f^2$$

where S_i = the distance of the image to the principal focus (F)

S_0 = the distance of the object to the principal focus

f = the focal length

The **Magnification**, m, is:

$$m = \frac{h_i}{h_0} = \frac{f}{S_0} = \frac{S_i}{f}$$

In any optical system where images are formed from objects, the ratio of the image height, h_i, to the object height, h_o is known as the magnification, m. For a plane mirror, the height of the image is the same as the height of the object, so the magnification is simply m = h_i h_o = 1. If the magnification is greater than 1, the image is larger than the object and is said to be magnified. If the magnification is less than 1, the image is smaller than the object so the image is said to be diminished.

Refraction

When light travels from a low optically dense medium, such as air, into high optically dense medium, such as glass, it slows down. The greater the increase in optical density, the greater the decrease in speed of light. This is described as an inversely proportional relationship.

$$\frac{refractive\ index\ for\ medium\ 1}{refractive\ index\ for\ medium\ 2} = \frac{speed\ of\ light\ in\ medium\ 2\ (ms^{-1})}{speed\ of\ light\ in\ medium\ 1\ (ms^{-1})}$$

$$\frac{n_1}{n_2} = \frac{v_2}{v_1}$$

If the incident ray strikes the boundary at an angle, then this change in speed also causes the ray to change direction. The light is described as being **refracted**

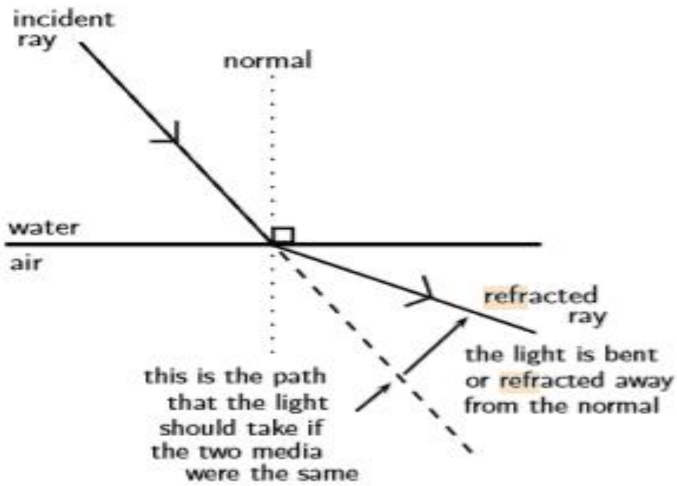


Figure 1: Light is moving from an optically dense medium to an optically less dense medium. Light is refracted away from the normal.

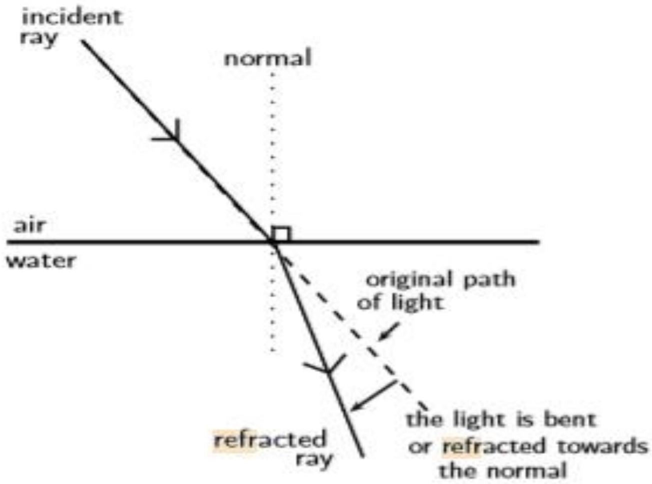


Figure 2: Light is moving from an optically less dense medium to an optically denser medium. Light is refracted towards the normal.

Refraction The changing of a light ray's direction (loosely called bending) when it passes through variations in matter is called refraction.

Refractive Index

Which is easier to travel through, air or water? People usually travel faster through air. So does light! The speed of light and therefore the degree of bending of the light depends on the refractive index of material through which the light passes. The *refractive index* (symbol n) is the ratio of the speed of light in a vacuum to its speed in the material. You can think of the refractive index as a measure of how difficult it is for light to get through a material.

Speed of Light

The symbol c is used to represent the speed of light in a vacuum. c = 299 792 485 $m \cdot s^{-1}$. For purposes of calculation, we use 3×10^8 $m \cdot s^{-1}$. A vacuum is a region with no matter in it, not even air. However, the speed of light in air is very close to that in a vacuum.

Refractive Index: The refractive index (symbol n) of a material is the ratio of the speed of light in a vacuum to its speed in the material and gives an indication of how difficult it is for light to get through the material.

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

where n = refractive index (no unit)

c = speed of light in a vacuum (3.00×10^8 $m \cdot s^{-1}$)

v = speed of light in a given medium ($m \cdot s^{-1}$)

The Law of Refraction

Law 1 For a particular colour of light, the ratio of the sine of the angle is inversely proportional to the ration of the refractive index as the ray travels from one medium to the other, so we have:

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

This is also known as Snell's Law.

Law 2 The incident ray, the normal and the refracted ray all lie on the same plane.

Combining Snell's Law and the relationship between velocity and refractive index gives us:

$$\frac{n_1}{n_2} = \frac{v_2}{v_1} = \frac{\sin \theta_2}{\sin \theta_1}$$

Total Internal Reflection and Critical Angle

When light travels from a high optically dense to a low optically dense medium, the ray is refracted away from the normal and a weak ray is refracted internally back into the denser medium.

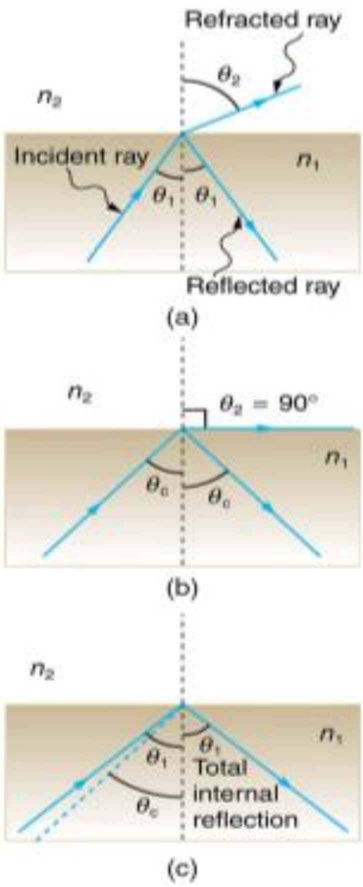


Figure 3: (a) A ray of light crosses a boundary where the speed of light increases and the index of refraction decreases. That is, $n_2 < n_1$. The ray bends away from the perpendicular. (b) The critical angle is the one for which the angle of refraction is. (c) Total internal reflection occurs when the incident angle is greater than the critical angle.

As the angle of incidence (θ_1) increases so does the angle of refraction (θ_2), until a certain angle of incidence is reached, called the **critical angle** (θ_c), at which point the angle of refraction $\theta_1 = 90^{\circ}$.

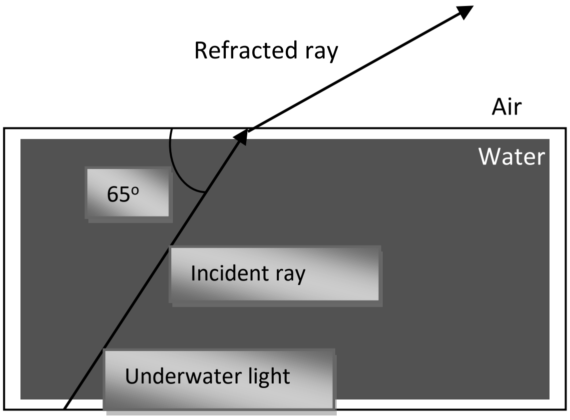
The critical angle can be calculated by comparing the refractive index of the two media.

$$\sin\theta_c = \frac{n_2}{n_1}$$

For angles of incidence greater than this critical angle (θ_c), the refracted ray disappears and all the light is **totally internally reflected** resulting in a bright reflected ray.

<u>Example:</u> The Laws of Refraction

A ray from a swimming pool light is incident upon the surface of the water at an angle of 65 ° to the surface, as shown in the diagram. Calculate the angle of refraction of the ray in the air.



Absolute refractive index of air, n_a = 1.00
Absolute refractive index of water, n_w = 1.33

<u>Solution</u>

Angles must always be measured to the normal. Whenever an angles is given that is measured to the surface we must first determine the incident angles as measured to the normal.

<u>Given</u>: $n_a = 1.00$

$n_w = 1.33$

$angle\ to\ the\ surface = 65^{\circ}$

Unknown: θ_a

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

Substitute: θ_w must be measured to the normal

$$\theta_w = 90 - 65 = 25°$$

$$n_w \sin\theta_w = n_a \sin\theta_a$$

$$1.33 \sin 25 = 1.00 \sin\theta_a$$

$$\sin\theta_a = \frac{1.33 \sin 25}{1.00} = 0.562$$

$$\theta_a = \sin^{-1}(0.562)$$

$$\theta_a = 34° \ (2s.f\ due\ to\ the\ angle)$$

Consider your answer: When the ray enters the air it will speed up, and since the angle of refraction is **proportional** to the velocity, we would expect the angle to get bigger. This agrees with our solution.

Activity 1.3

1. Use the mirror formula $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$ to solve the following problems:
    a. Geeta places a concave mirror 60 cm away from a candle and focuses a real image onto a piece of card 40 cm away from the mirror. Determine the focal length of the mirror.

    b. Mathew is standing 4.8 m away from a shop security mirror. The mirror is convex and has a focal length of 7.2 m. Calculate the distance of Mathew's virtual image from the pole of the mirror.

2. Use $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$ and $m = \frac{h_i}{h_0} = \frac{v}{u}$ to solve the following problems:
    a. A concave mirror of focal length 18 cm is used to produce a real image of an object placed 42 cm from the pole of the mirror. Given that object is 9.0 cm tall, determine:
        i. The distance of the image from the mirror.
        ii. The magnification.
        iii. The size of the image.

3. Define Refraction.

4. State the law of refraction.

5. By considering these equations, describe what will happen in the situations that follow, stating which equation informed your decision:

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} \qquad \frac{n_1}{n_2} = \frac{v_2}{v_1} \qquad \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

    a. A ray is incident upon a more optically dense medium normal to the surface ($\theta_i = 0°$). Describe the change in velocity and angle to the normal in the new medium.

    b. A ray enters a new medium at an angle and speeds up. Describe the change in refractive index and angle to the normal.

    c. A ray enters a new medium and the angle to the normal decreases. Describe the change in velocity and refractive index.

6. Use these equations to solve the problems that follow:

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} \qquad \frac{n_1}{n_2} = \frac{v_2}{v_1} \qquad \frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

   a. A ray of yellow light is travelling through water at a speed of 2.25 x 10^8 ms^{-1} when it is incident upon a street of ice, causing it to speed up to 2.29 x 10^8 ms^{-1}. Calculate the refractive index of ice. (Absolute refractive index of water, n_w = 1.33)

   b. A ray of yellow light in air is incident upon a glass block at an angle of 57.8^o to the normal and is refracted at an angle of 31.9^0. Calculate the absolute refractive index of the glass. (Absolute refractive index of air, n_a = 1.0)

   c. A ray of yellow light in water is incident upon the surface at an angle of 22.0^o to the normal and is refracted at an angle of 29.9^o to the normal. Calculate the speed of yellow light in the water. (Speed of light in air, v_a =3.0 x 10^8 ms^{-1}.)

   d. Crystalline silicon has a refractive index of n_s = 3.97 for yellow light. Determine the change in the speed of light if a ray of yellow light travels from air into a sheet of crystalline silicon. (Absolute refractive index of air, n_a = 1.0008; velocity of light in air, v_a = 2.996 x 10^8 m/s.)

7. Define the following as they relate to refraction:
   a. Critical angle

   b. Total internal reflection