Section 1.1.3 – Refraction of Light

Refraction of Light

Refraction is the **bending of light** as it passes from one material into another, as seen in Figure 1 below. Light travels at **different speeds in different materials** and this is what causes the light to bend. The amount or extent of bending depends upon the relative speeds of light in each material.

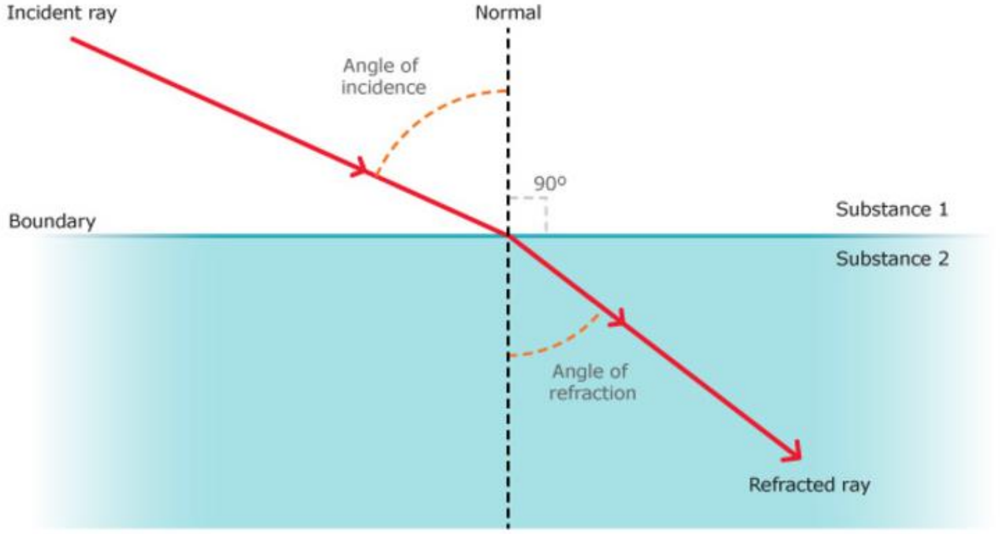


Figure 1 Refraction of light

The speed of light through the medium depends upon the **mediums optical density**, commonly measured as a refractive index.

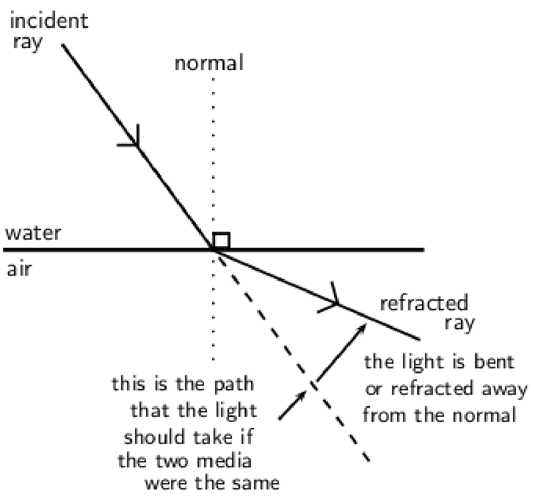


Figure 2A *Refraction away from normal*
Optical density (water) > Optical density (air)
∴incident light bends **away from the normal**

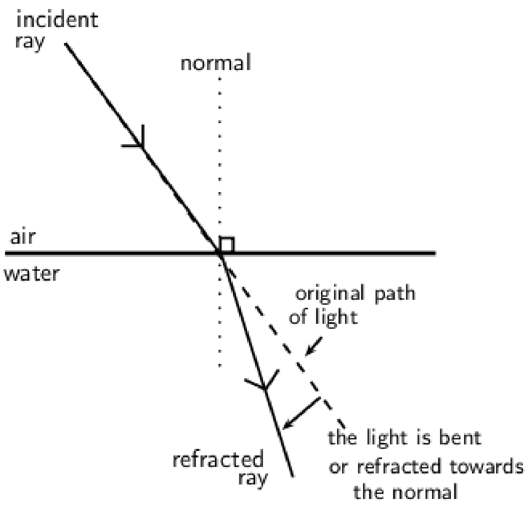


Figure 2B *Refraction towards normal*
Optical density (air) < Optical density (water)
∴incident light bends **towards the normal**

Snell's Law

Dutch physicist Willebrord Snelius (Willebrand Snell) found that the ratio of the sine of the **incident (*i*) angle** to that of the **refracted (r) angle** was constant for all given angles during refraction.

He discovered that:

$$\frac{\sin(i)}{\sin(r)} = constant$$

Snell discovered that the extent to which light diffracted when passing between two mediums depended upon the **mediums being used**.

The quantitative measure of how much a medium bends light is called its **refractive index**. It is determined by calculating the **ratio of speed of light in the two media**. In order to compare different materials effectively, the speed of light in a material is compared against the speed of light in a vacuum.

$$n_{medium} = \frac{v_{light\ in\ vacuum}}{v_{light\ in\ medium}}$$

NB: The speed of light in a vacuum is used as a reference speed
$v_{light\ in\ vacuum}$ = 3.00×10^8 ms^{-1}

Example.1

Given the speed of light in crown glass is 1.97×10^8 ms^{-1}, calculate the refractive index of crown glass.

$n_{crown\ glass}$ = ?

$v_{light\ in\ crown\ glass}$ = 1.97×10^8 ms^{-1}

$v_{light\ in\ vacuum}$ = 3.00×10^8 ms^{-1}

$$n_{crown\ glass} = \frac{v_{light\ in\ vacuum}}{v_{light\ in\ crown\ glass}}$$

$$n_{crown\ glass} = \frac{3.0 \times 10^8}{1.97 \times 10^8}$$

$= 1.52$

Example.2

Given the refractive index of ice is 1.31, calculate the speed that light travels in ice?

$v_{light\ in\ ice}$ = ?

n_{ice} = 1.31

$v_{light\ in\ vacuum}$ = 3.00×10^8 ms^{-1}

$$n_{ice} = \frac{v_{light\ in\ vacuum}}{v_{light\ in\ ice}}$$

$$\therefore v_{ice} = \frac{v_{light\ in\ vacuum}}{n_{ice}}$$

$$= \frac{3.00 \times 10^8}{1.31}$$

$= 2.29 \times 10^8$ ms^{-1}

Relative refractive index is a measure of how much light bends when travelling from one substance into any other substance.

Absolute refractive index of a substance is the relative refractive index for light travelling from a vacuum into the substance. This measurement is commonly referred to as "the refractive index".

Material	Refractive Index
Air	1.0003
Water	1.333
Glycerin	1.473
Immersion Oil	1.515
Glass (Crown)	1.520
Glass (Flint)	1.656
Zircon	1.920
Diamond	2.417
Lead Sulfide	3.910

Table.1 *Refractive indices*

Snell eventually derived the following equation, which is today referred to as Snell's Law.

$$\boldsymbol{n_1 \sin(i) = n_2 \sin(r)}$$

Where n_1 is the refractive index of the incident medium (medium 1)
n_2 is the refractive index of the refractive medium (medium 2)
i is the angle of incidence (°)
r is the angle of refraction (°)

Example.3

Calculate the angle of incidence for a ray of light which travels from air (n_1 =1.00) into glass (n_2 = 1.50) forming an angle of refraction of 30°.

i = ?
r = 30°
n_{air} = 1.00
n_{glass} = 1.50

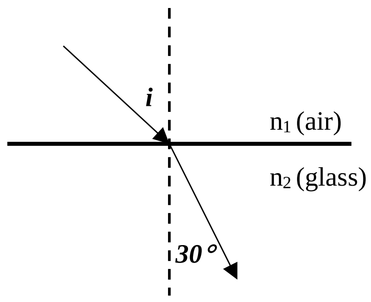
$$n_1 \sin(i) = n_2 \sin(r)$$

$$\therefore \sin(i) = \frac{n_2 \sin(r)}{n_1}$$

$$\therefore i = sin^{-1}\left(\frac{n_2 \sin(r)}{n_1}\right)$$

$$i = sin^{-1}\left(\frac{1.50 \times \sin(30°)}{1.00}\right)$$

$$= 48.6°$$



Example.4

Calculate the refractive index of an unknown material X if a ray of light travelling from air at an angle of 45°, enters into material X at an angle of 35°

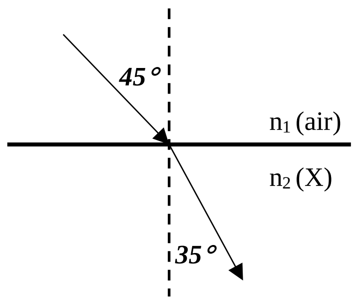
n_X = ?
n_{air} = 1.00
i = 45°
r = 35°

$$n_1 \sin(i) = n_2 \sin(r)$$

$$\therefore n_2 = \frac{n_1 \sin(i)}{\sin(r)}$$

$$\therefore n_2 = \frac{1.00 \times \sin(45°)}{\sin(35°)}$$

$$\therefore n_2 = 1.23$$



Example.5

Calculate the angle of refraction for a ray of light which travels from Flint glass (n_1 =1.656) into air (n_2 = 1.00) given it has an angle of incidence of 25°.

r = ?
i = 25°
n_{flint}= 1.656
n_{air} = 1.00

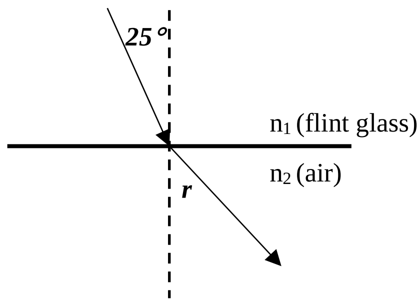
$$n_1 \sin(i) = n_2 \sin(r)$$

$$\therefore \sin(r) = \frac{n_1 \sin(i)}{n_2}$$

$$\therefore r = sin^{-1}\left(\frac{n_1 \sin(i)}{n_2}\right)$$

$$r = sin^{-1}\left(\frac{1.656 \times \sin(25°)}{1.00}\right)$$

= 44.4°



Example.6

Calculate the refractive index of an unknown material Y if a ray of light travelling from material Y at an incident angle of 30°, refracts at an angle of 61° in water (n_2 = 1.333)

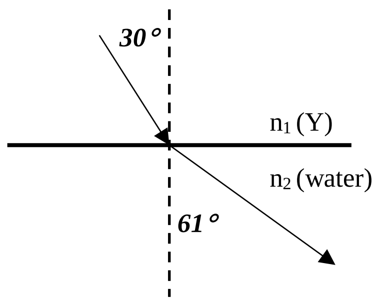
n_Y = ?
n_{water} = 1.333
i = 30°
r = 61°

$$n_1 \sin(i) = n_2 \sin(r)$$

$$\therefore n_1 = \frac{n_2 \sin(r)}{\sin(i)}$$

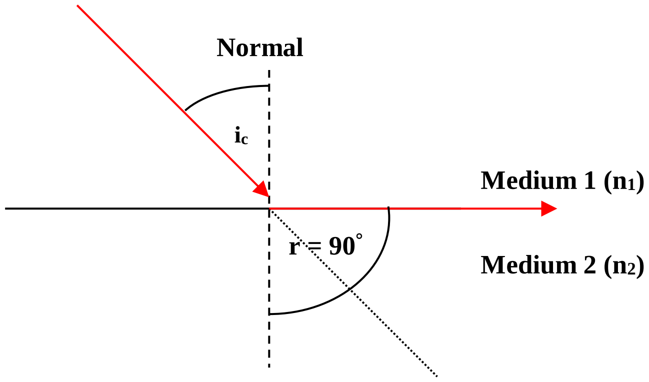
$$\therefore n_1 = \frac{1.333 \times \sin(61°)}{\sin(30°)}$$

$$\therefore n_1 = 2.33$$



Total Internal Reflection and Critical Angle

It is possible for light travelling from one medium into a second, **of less optical density**, to refract to such an extent that it **does not escape** out of the second medium, but rather "grazes" along the surface of the material.



The incident angle at which this phenomenon occurs is the **critical angle (i_c).** An incident angle greater than the critical angle will produce **total internal reflection**, whereby no light enters the second medium at all.

NB: The critical angle refers to the smallest angle of incidence for which total internal reflection occurs.

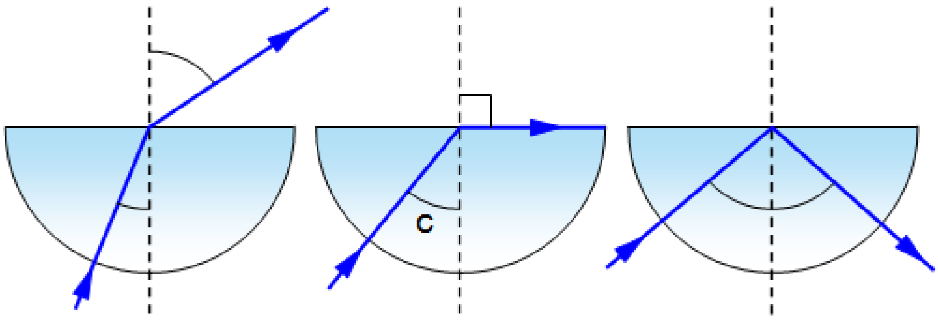


Figure.3 *Refraction. Critical angle and total internal reflection*

- At $i < i_c$ the refracted ray enters medium 2
- At i_c the refracted ray is refracted at exactly 90° and grazes along the boundary between the two medium
- At $i > i_c$ there is no refracted ray entering medium 2, rather the incident ray is reflected back into medium 1. The process is called total internal reflection.

Using Snell's Law

$$i = sin^{-1}\left(\frac{n_2 \sin(r)}{n_1}\right)$$

sin (90°) = 1

For the critical angle, $r = 90°$

$$\therefore i_c = sin^{-1}\left(\frac{n_2 \sin(90)}{n_1}\right)$$

$$\boxed{i_c = sin^{-1}\left(\frac{n_2}{n_1}\right)}$$

Example.7

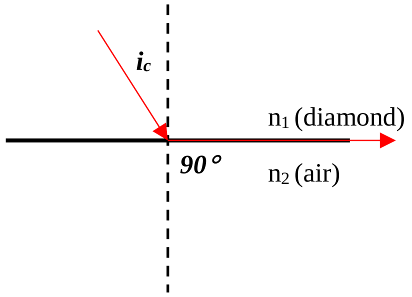
Calculate the critical angle (i_c) for light travelling from diamond into air.
Refer to Table.1 for the appropriate refractive indices.

i_c = ?
r = 90°
$n_{diamond}$ = 2.417
n_{air} = 1.0003

$$i_c = sin^{-1}\left(\frac{n_2}{n_1}\right)$$

$$i_c = sin^{-1}\left(\frac{1.0003}{2.417}\right)$$

$$i_c = 24.45°$$



Colour Dispersion in Prisms

Each colour of light has a slightly different **frequency and wavelength.**

COLOUR	ENERGY	FREQUENCY in Tera Hertz*	WAVELENGTH in nanometres
red	lowest	435 - 495	685 - 605
orange		495 - 515	605 - 585
yellow		515 - 535	585 - 560
green	middle	535 - 630	560 - 475
blue		630 - 660	475 - 455
indigo		660 - 680	455 - 440
violet	highest	680 - 740	440 – 405

* a Tera Hertz is a billion billion cycles (or complete wavelengths) passing by per second

***Table.2** Comparison of frequency and wavelength of coloured light*

White light is what we see when all the wavelengths of visible light hit our eyes in **equal amounts.**

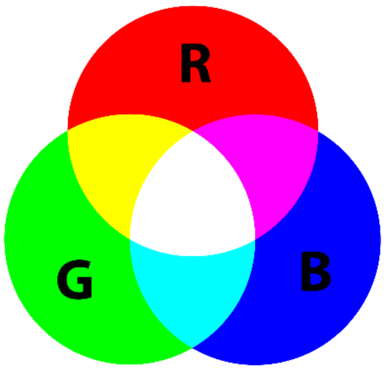


***Figure.3** The production of white light*

The refractive index is slightly higher for high frequency (violet) light than low frequency (red) light.

Accordingly, violet light changes direction towards normal more than red light when entering a higher refractive index medium. This can be seen in Figure 4 below.

NB: Blue bends best!

Violet light also changes direction away from normal more than red light when entering a lower refractive index medium.

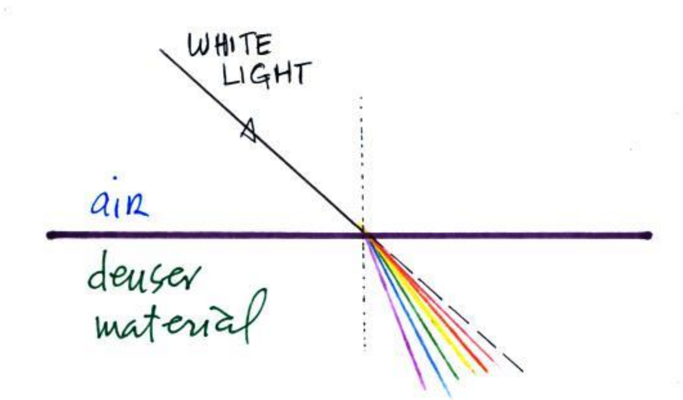


Figure.4 *the refraction of different colours of light*

Colour dispersion is the separation of white light into its component colours due to the different amounts that each colour refracts, as can be seen in Figure.5 below

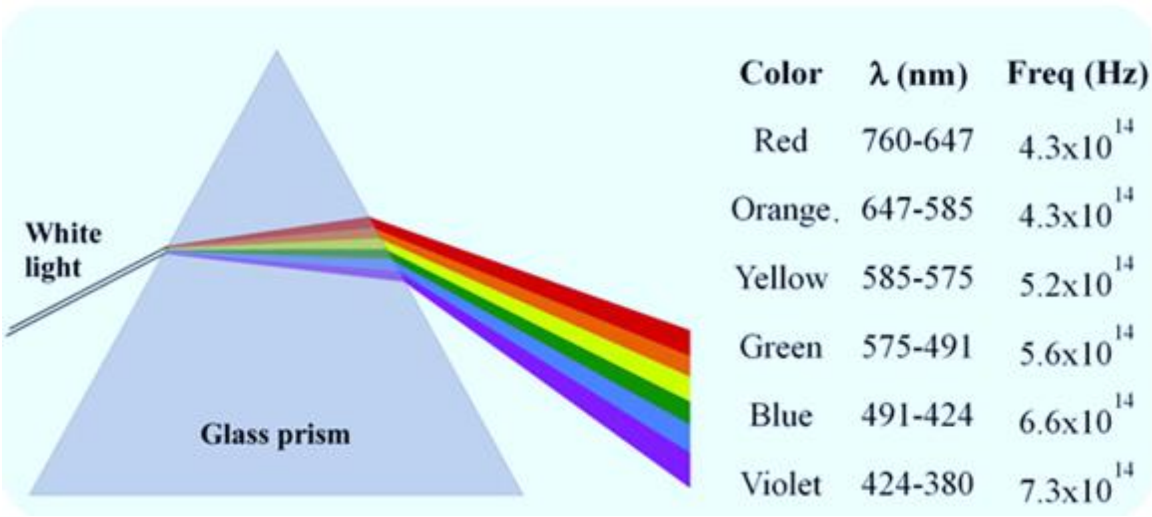
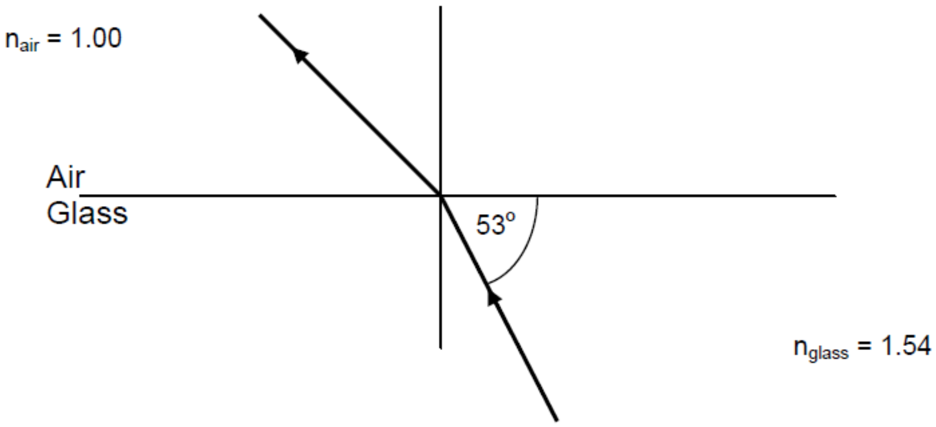


Figure.5 *the dispersion of colour within a prism*

Exam Styled Questions

Questions 1 to 3 refer to the following information.

Light in glass travels into air as indicated on the following diagram.



Question 1

What is the angle of incidence?

The angle of incidence is measured between the incident ray and the normal. The normal is at 90° to the surface. ∴ angle i = 90 – 53 = 37°

37 °

Question 2

Use Snell's Law to calculate the angle of refraction.

$n_1 = 1.54$ $\quad$ $n_1 \sin(i) = n_2 \sin(r)$

$n_2 = 1.00$ $\quad$ $\therefore r = \sin\text{-}1\left(\frac{n_1 \sin(i)}{n_2}\right)$

$i = 37°$ $\quad$ $= \sin\text{-}1\left(\frac{1.54 \times \sin(37^\circ)}{1.00}\right)$

$r = ?$ $\quad$ $= 68°$

68 °

Question 3

Calculate the critical angle (i_c) for the glass – air interface.

$n_1 = 1.54$ $\quad$ $\sin(i_c) = n_2/n_1$

$n_2 = 1.00$ $\quad$ $\therefore\ i_c = \sin^{-1}(n_2/n_1)$

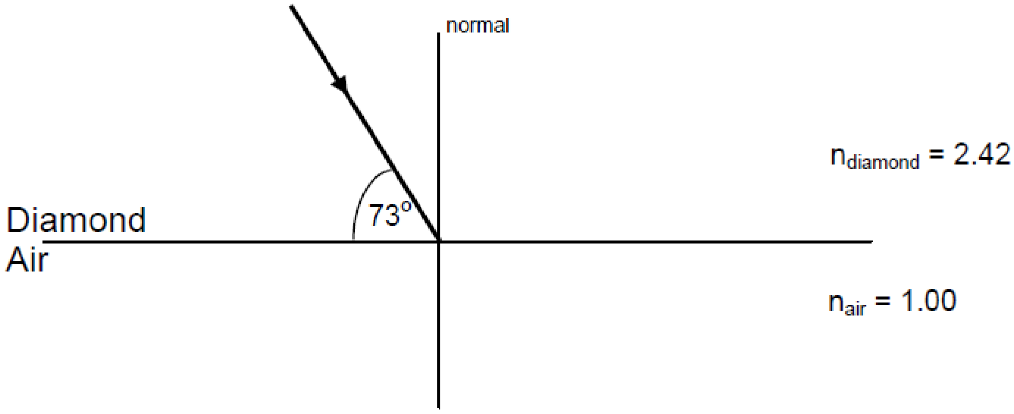
$i_c = ?$ $\quad$ $= \sin^{-1}(1.00/1.54)$

$= 40.49°$

40.5 °

Questions 4 to 7 refer to the following information.

Light travels from diamond into air as indicated on the following diagram.



Question 4

What is the angle of incidence?

The angle of incidence is measured between the normal and the incident ray.

angle i = 90 – 73 = 17°

17 °

Question 5

What is the critical angle for a diamond-air interface?

$n_1 = 2.42$ $\sin(i_c) = n_2/n_1$

$n_2 = 1.00$ $\therefore i_c = \sin^{-1}(n_2/n_1)$

$i_c = ?$ $= \sin^{-1}(1.00/2.42)$

$= 24.41°$

24.4 °

Question 6

Use Snell's Law to calculate the angle of refraction for this ray of light.

$n_1 = 2.42$ $n_1 \sin(i) = n_2 \sin(r)$

$n_2 = 1.00$ $\therefore r = \sin^{-1}\left(\frac{n_1 \sin(i)}{n_2}\right)$

$i = 17°$ $= \sin^{-1}\left(\frac{2.24 \times \sin(17^\circ)}{1.00}\right)$

$r = ?$ $= 45°$

45 °

Question 7

The speed of light in air is 3.00×10^8 ms^{-1}. What is the speed of light in diamond? The speed of light is slower in diamond than in air.

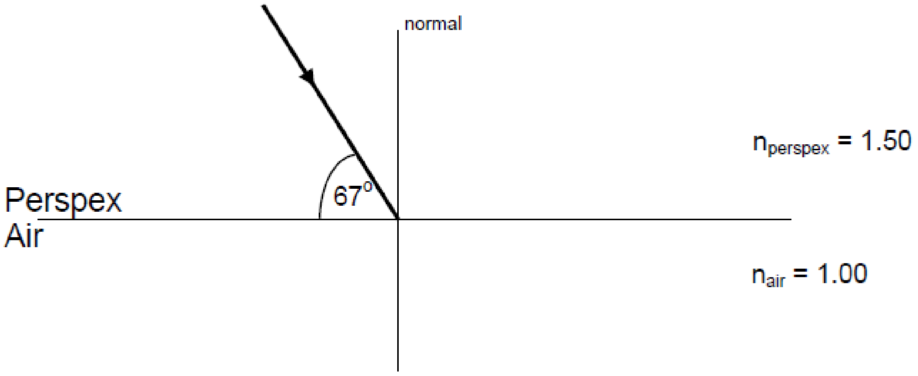
v_1 = ?
$v_2 = 3.0 \times 10^8$ ms^{-1}
$n_1 = 2.42$
$n_2 = 1.00$

$v_1/v_2 = n_2/n_1$
$\therefore v_1 = v_2 \times n_2/n_1$
$= 3.0 \times 10^8 \times (1.00/2.42)$
$= 1.24 \times 10^8$ ms^{-1}

1.24×10^8 ms^{-1}

Questions 8 and 9 refer to the following information.

Light travels from perspex (a transparent plastic) into air as indicated on the following diagram.



Question 8

Use Snell's Law to calculate the angle of refraction for this ray of light.

$n_1 = 1.50$
$n_2 = 1.00$
$i = 23°$
r = ?

$n_1 \sin(i) = n_2 \sin(r)$
$\therefore r = \sin^{-1}(\frac{n_1 \sin(i)}{n_2})$
$= \sin^{-1}(\frac{1.50 \times \sin(23°)}{1.00})$
$= 35.9°$

35.9 °

Question 9

What is the critical angle for a perspex-air interface?

$n_1 = 1.50$
$n_2 = 1.00$
i_c = ?

$\sin(i_c) = n_2/n_1$
$\therefore i_c = \sin^{-1}(n_2/n_1)$
$= \sin^{-1}(1.00/1.50)$
$= 41.8°$

41.8 °

Questions 10 and 11 refer to the following information.

Blue light of frequency 6.5×10^{14} Hz travels through a sample of flint glass at 1.9×10^{8} ms^{-1}.

Question 10

What is the refractive index for blue light in this sample of flint glass?

$n_1 = ?$

$n_2 = 1.00$

$v_1 = 1.9 \times 10^8$ ms^{-1}

$v_2 = 3.0 \times 10^8$ ms^{-1}

$v_1/v_2 = n_2/n_1$

$\therefore n_1 = n_2 \times v_2/v_1$

$= 1.00 \times (3.0 \times 10^8/1.9 \times 10^8)$

$= 1.58$

1.58

Question 11

What is the wavelength of blue light in flint glass?

$v = f \times \lambda$

$\therefore \lambda = v/f$

$= 1.9 \times 10^8/6.5 \times 10^{14}$

2.9×10^{-7} m