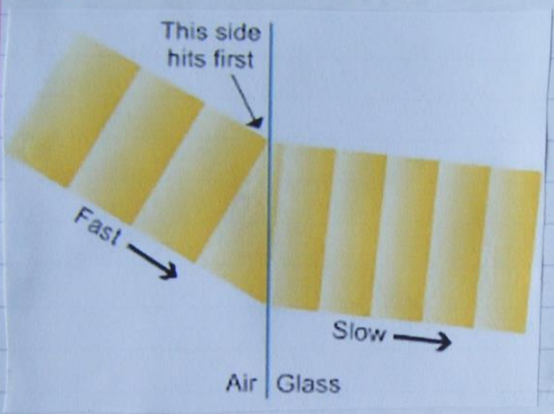
Refraction of light - B McMULLEN ①

Refraction is the change in the speed of light when passing from one medium to another.

eg Air → Glass



Refraction

When light moves from one medium to another it will bend, but its definition is based on the change of speed.

$V_A = 3 \times 10^8 ms^{-1}$ $V_G = 2 \times 10^8 ms^{-1}$

If light passes from air into water then its speed will reduce from $V_A = 3 \times 10^8 ms^{-1}$ to $V_W = 2 \cdot 26 \times 10^8 ms^{-1}$.

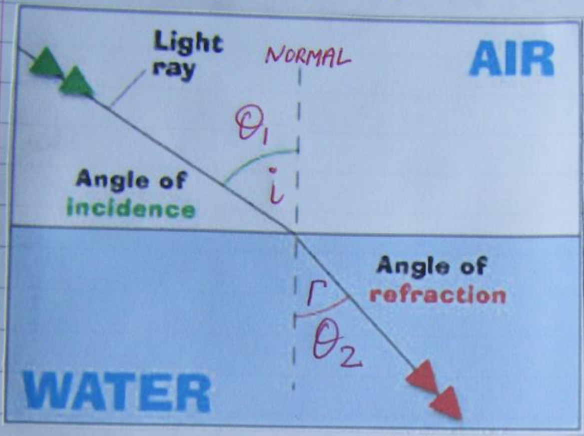
Why?

Air → Water	Air → Glass
$3 \times 10^8 ms^{-1} \rightarrow 2 \cdot 26 \times 10^8 ms^{-1}$	$3 \times 10^8 ms^{-1} \rightarrow 2 \times 10^8 ms^{-1}$
$\div 1 \cdot 33$	$\div 1 \cdot 50$.

The factor by which the speed of light reduces from air into a medium is called the refractive index of the medium

Conclusion

The denser the medium, the slower the speed of light in the medium.



angle of incidence (i)
>
angle of refraction (r)

$i > r$

$\therefore \theta_1 > \theta_2$

* All angles are measured from the normal *

* When light passes from a less dense medium to a more dense medium then it will bend towards the normal *
ie $\theta_1 > \theta_2$

** Also vice-versa will apply here ie when light passes from a more dense medium to a less dense medium then it will bend away from the normal *

ie θ_1 is always used as the less dense medium and θ_2 as the more dense medium!!

ie $\theta_1 \Rightarrow$ Air and $\theta_2 \Rightarrow$ Non air medium

Snell's Law

$$n = \frac{\sin\theta_1}{\sin\theta_2}$$

- n → Refractive index of the non-air medium (No Units!!)
- $\sin\theta_1$ → Sine of the angle in air
- $\sin\theta_2$ → Sine of the angle in the non-air medium.

Willebrord Snell
(1580-1626)

IMPORTANT POINTS

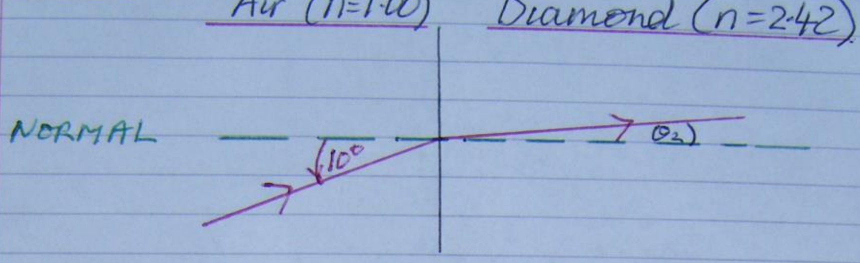
- $1 \leq n \leq 3$
- n has no units
- n is always written to 2dp's.

As we mentioned earlier the denser the medium the greater its refractive index.

Refractive indices for different mediums.

Medium	Refractive index, n
Air	1·00
Water	1·33
Glass	1·50
Diamond	2·42

Ex1



Q

a) Calculate θ_2, the angle of light in Diamond.

b) If Diamond is replaced by glass then estimate the angle of the light in the glass in this case and explain why?

A

a) $\theta_2 < 10^\circ$ as it is a denser medium than air.

$n = 2.42$ ie always use the refractive index of the non-air medium here!!
$\theta_1 = 10^\circ$
$\theta_2 = ?$

$$n = \frac{\sin\theta_1}{\sin\theta_2} \Rightarrow 2.42 = \frac{\sin 10^\circ}{\sin\theta_2}$$

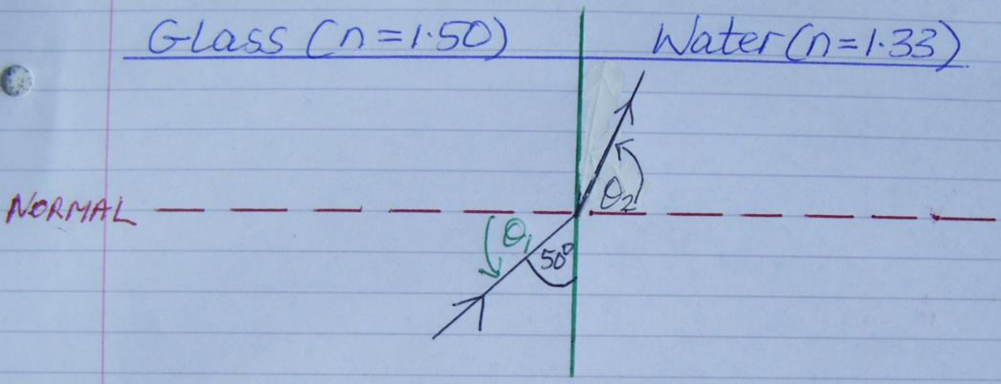
$$\Rightarrow \sin\theta_2 = \frac{\sin 10^\circ}{2.42} = 0.0718$$

$$\therefore \theta_2 = \sin^{-1}(0.0718) = \underline{4.1^\circ}$$

b) θ_2 - angle in glass > 4.1°

This is due to glass being less dense than Diamond with a smaller refractive index.

Ex 2 → Light moving between 2 non-air mediums.



Q Calculate θ_2, the angle of light in water.

A $\theta_1 = 90° - 50° = \underline{40°}$ (Always measure angles from the normal!!)

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$ ⇐ Not in DB!!

$\Rightarrow 1.50 \sin 40° = 1.33 \sin\theta_2$

$\Rightarrow \sin\theta_2 = \frac{1.50 \sin 40°}{1.33} = 0.725$

$\Rightarrow \theta_2 = \sin^{-1}(0.725) = \underline{46.5°}$

$\theta_2 = 46.5^\circ$ makes sense as water is less dense than glass and so it will have a larger angle than in glass ie $>40^\circ$.

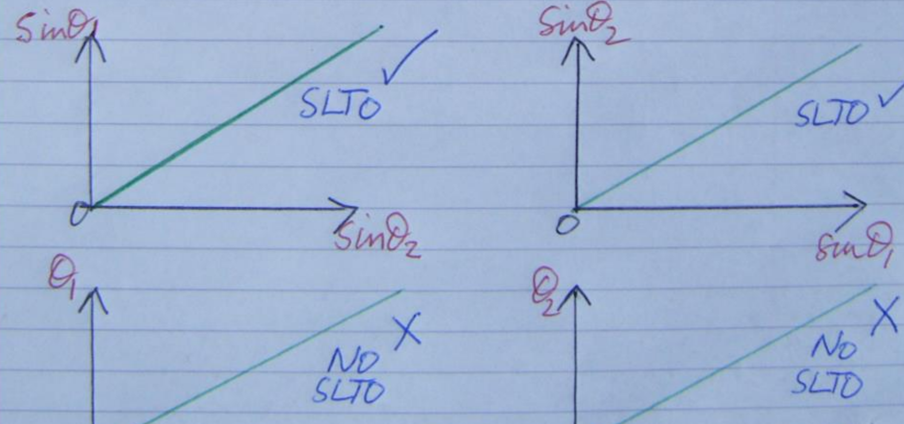
Snell's Law Graphically

$n = \frac{\sin\theta_1}{\sin\theta_2}$, where n is the refractive index of the medium which is a constant.

$\Rightarrow \sin\theta_1 = n \sin\theta_2$

$\Rightarrow \sin\theta_1 = k \sin\theta_2$

$\Rightarrow \boxed{\sin\theta_1 \propto \sin\theta_2}$



The bottom two graphs do not produce an SLTO as θ_1 is not directly proportional to θ_2.

Extending Snell's Law

When light moves from one medium to another its frequency always stays constant.

From the wave equation at NAT5.

$$v = f.\lambda$$

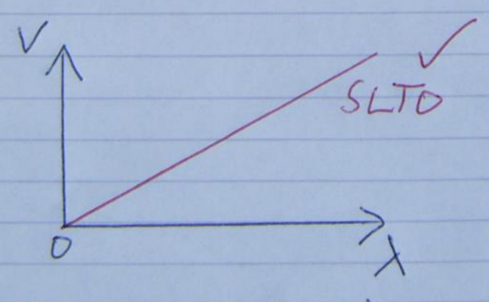
- v → Speed/Velocity (ms^{-1})
- f → frequency (Hz)
- λ → Wavelength (m)

If f is a constant then

$$v = f\lambda \Rightarrow v = k\lambda \Rightarrow \boxed{v \propto \lambda}$$

ie wave speed/velocity is directly proportional to the wavelength of the wave.

ie

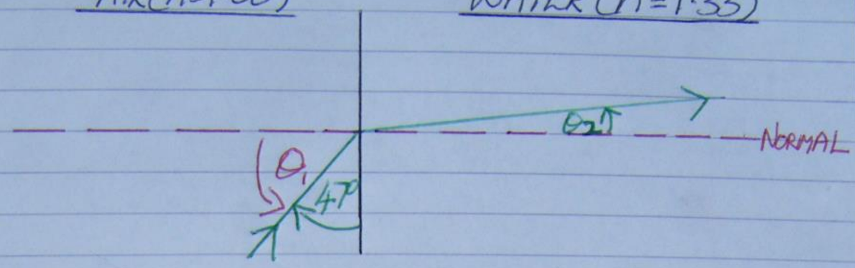


The refractive index n can be measured using $n = \frac{V_1}{V_2}$ and $n = \frac{\lambda_1}{\lambda_2}$

$$\Rightarrow \boxed{n = \frac{\sin\theta_1}{\sin\theta_2} = \frac{V_1}{V_2} = \frac{\lambda_1}{\lambda_2}}$$

1 → AIR
2 → MEDIUM.

Ex3



Red light of wavelength 660nm is passed from air through to water. Calculate or find:

a) θ_1 and θ_2

$$\theta_1 = 90^\circ - 47^\circ = 43^\circ$$

$$\theta_2 = ? \quad n = \frac{\sin\theta_1}{\sin\theta_2} \Rightarrow 1.33 = \frac{\sin 43^\circ}{\sin\theta_2}$$

$$\Rightarrow \sin\theta_2 = \frac{\sin 43^\circ}{1.33} = 0.513$$

$$\Rightarrow \quad \theta_2 = \sin^{-1}(0.513) = 30.8^\circ$$

b) The speed of light in water

$$n = \frac{V_1}{V_2} \Rightarrow 1.33 = \frac{3\times10^8}{V_2}$$

$$\Rightarrow V_2 = \frac{3\times10^8}{1.33} = 2.26\times10^8\,ms^{-1}$$

c) The wavelength of light in water.

$n = \frac{\lambda_1}{\lambda_2} \Rightarrow 1{\cdot}33 = \frac{660 \times 10^{-9}}{\lambda_2}$

$\Rightarrow \lambda_2 = \frac{660 \times 10^{-9}}{1{\cdot}33} = 496 \times 10^{-9} = 496\,nm$

d) The frequency of the light in air and in water.

$f_A = f_W$.

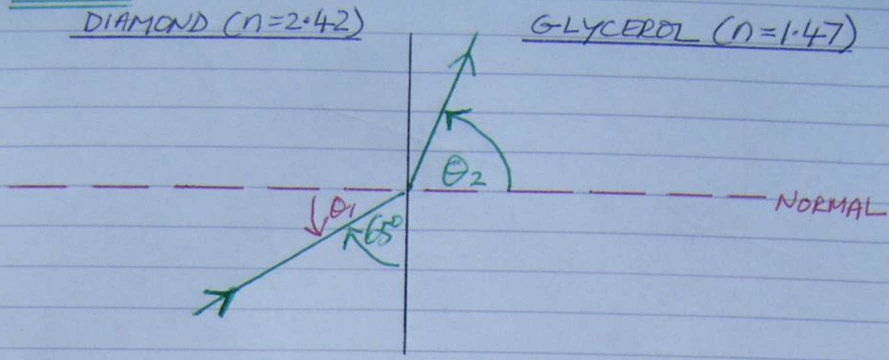
$v = f\lambda \Rightarrow f_A = \frac{V_A}{\lambda_A} = \frac{3 \times 10^8}{660 \times 10^{-9}} = 4{\cdot}55 \times 10^{14}\,Hz$

To check use

$f_W = \frac{V_W}{\lambda_W} = \frac{2{\cdot}26 \times 10^8}{496 \times 10^{-9}} = 4{\cdot}55 \times 10^{14}\,Hz$.

∴ QED

Ex4



Green light of wavelength 550nm is passed from Diamond through to Glycerol as shown above.
Calculate or find:

a) θ_1 and θ_2

$\theta_1 = 90^\circ - 65^\circ = 25^\circ$

θ_2 =? $\Rightarrow \quad n_1 \sin\theta_1 = n_2 \sin\theta_2$

$\Rightarrow 2.42 \sin 25^\circ = 1.47 \sin\theta_2$

$\Rightarrow 1.02 = 1.47 \sin\theta_2$

$\Rightarrow \sin\theta_2 = \frac{1.02}{1.47} = 0.694$

$\Rightarrow \theta_2 = \sin^{-1}(0.694) = 43.9^\circ$

b) Calculate the speed of light in

i) Diamond
ii) Glycerol.

Compare each of these mediums to air individually!!

i) Diamond

$$n = \frac{V_1}{V_2} \Rightarrow 2.42 = \frac{3 \times 10^8}{V_2}$$

$$\Rightarrow V_2 = \frac{3 \times 10^8}{2.42} = 1.24 \times 10^8 ms^{-1}$$

ii) Glycerol

$$n = \frac{V_1}{V_2} \Rightarrow 1.47 = \frac{3 \times 10^8}{V_2}$$

$$\Rightarrow V_2 = \frac{3 \times 10^8}{1.47} = 2.04 \times 10^8 ms^{-1}$$

c) Calculate the wavelength of the light in

i) Diamond
ii) Glycerol.

i) Diamond

$$n = \frac{\lambda_1}{\lambda_2} \Rightarrow 2.42 = \frac{550 \times 10^{-9}}{\lambda_2} \Rightarrow \lambda_2 = \frac{550 \times 10^{-9}}{2.42}$$

$$\therefore \lambda_2 = 227 \times 10^{-9} m = 227 nm$$

ii) Glycerol

$n = \frac{\lambda_1}{\lambda_2} \Rightarrow 1.47 = \frac{550 \times 10^{-9}}{\lambda_2}$

$\Rightarrow \lambda_2 = \frac{550 \times 10^{-9}}{1.47} = 374 \times 10^{-9} m = 374 nm$

d) Show that the frequency of the light in Diamond is the same as the frequency of the light in Glycerol.

Diamond

$V = f\lambda \Rightarrow f = \frac{V}{\lambda} = \frac{1.24 \times 10^{8}}{227 \times 10^{-9}} = 5.46 \times 10^{14} Hz$

Glycerol

$V = f\lambda \Rightarrow f = \frac{V}{\lambda} = \frac{2.04 \times 10^{8}}{374 \times 10^{-9}} = 5.46 \times 10^{14} Hz$

$\therefore f_{DIAMOND} = f_{GLYCEROL} = 5.46 \times 10^{14} Hz$

$\therefore$ QED

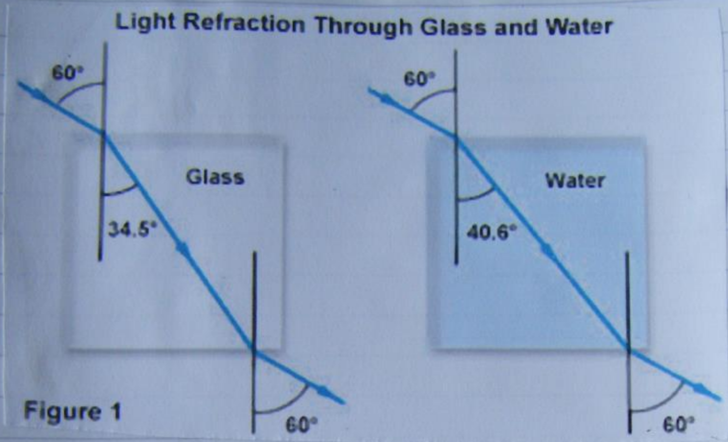
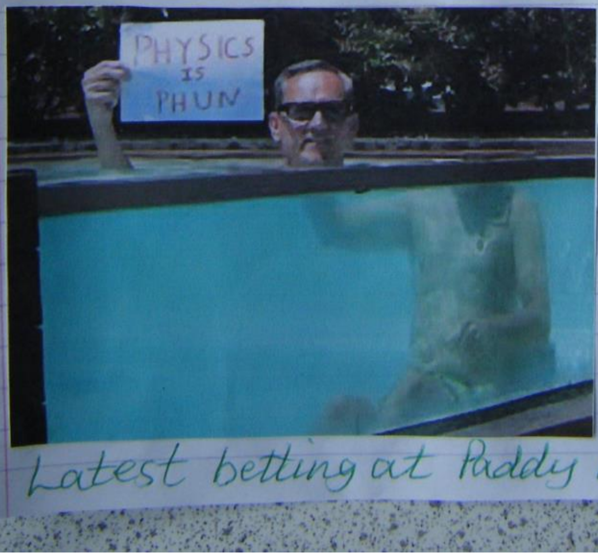


Figure 1 clearly shows that when light passes from a less dense medium (ie air) into a more dense medium (ie glass or water) it will bend towards the normal.

It can also be seen in figure 1 that the light entering and leaving each of the mediums (glass and water) are parallel.

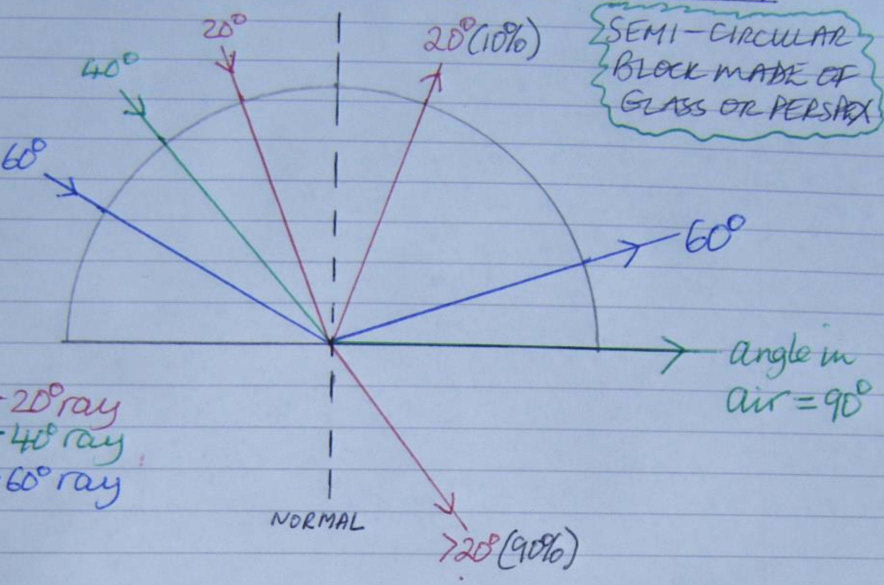


This shows refraction going mad!!

I would not fancy this chaps chances of passing Higher English!!

Latest betting at Paddy Power is 250/1!!

Total Internal Reflection (T.I.R)



- **20° ray of light**

$\theta_M = 20°$ ie $\theta_M < \theta_c$.

90% of the light Irradiance is refracted out into the air at an angle > 20° ie ≈ 30° in practice.

10% of the light Irradiance is totally internally reflected (T.I.R)

- **≈40° ray of light**

$\theta_M \approx 40°$ ie $\theta_M = \theta_c$

The light Irradiance moves out into the air at 90°.

$\theta_c \simeq 40°$ is called the critical angle of the glass or perspex.

The critical angle (θ_c) is the angle of light in a medium which will allow the light to come into the air at 90°.
(ie The light moves along the air/medium boundary).

* • <u>60° ray of light</u>

$\theta_M = 60°$ ie $\theta_M > \theta_c$

The ray of light will be Totally Internally Reflected (T.I.R) at the boundary between the two mediums.
ie In this case at 60°.

<u>The Critical Angle Equation</u>

From $n = \dfrac{\sin\theta_1}{\sin\theta_2}$

This is the angle in the medium which will allow light to pass into the air at 90°.

$\Rightarrow n = \dfrac{\sin 90°}{\sin\theta_c}$ $\Rightarrow$ As $\sin 90° = 1$

$\Rightarrow n = \dfrac{1}{\sin\theta_c}$ $\Rightarrow$ In DB!!

$$\boxed{\sin\theta_c = \frac{1}{n}}$$

Ex5

Q. Calculate the critical angles in water, glass and diamond which have the refractive indices of 1·33, 1·50 and 2·42 respectively.

A. **Water**

$\sin\theta_c = \frac{1}{n} = \frac{1}{1.33}$

$\sin\theta_c = 0.752$

$\Rightarrow \theta_c = \sin^{-1}(0.752)$

$\Rightarrow \theta_c = 48.8^\circ$

Glass

$\sin\theta_c = \frac{1}{n} = \frac{1}{1.50}$

$\Rightarrow \sin\theta_c = 0.667$

$\Rightarrow \theta_c = \sin^{-1}(0.667)$

$\Rightarrow \theta_c = 41.8^\circ$

Diamond

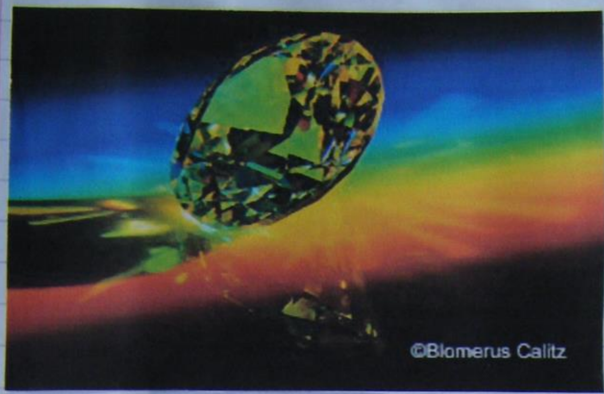
$\sin\theta_c = \frac{1}{n} = \frac{1}{2.42}$

$\Rightarrow \sin\theta_c = 0.413$

$\Rightarrow \theta_c = \sin^{-1}(0.413)$

$\Rightarrow \theta_c = 24.4^\circ$

* Conclusion ⇒ The higher refractive index n of a medium the lower the critical angle θ_c of the medium. *



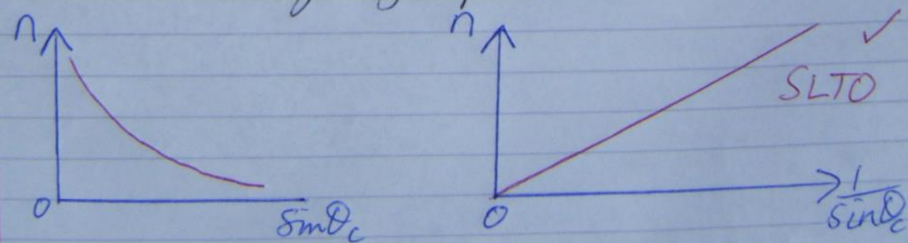
What are a girls best friend?

Diamonds of course!!

Diamonds have a very low critical angle which will produce a lot more total internal reflection (T.I.R) within its surfaces.

The refraction of white light inside the diamond will split the white light into the colours of the visible spectrum (ROYGBIV) and as they hit the surfaces at different angles this will produce the sparkle.

<u>Critical Angle Graphs.</u>



From $n = \frac{1}{\sin\theta_c}$ $\quad \cdot\ n \propto \frac{1}{\sin\theta_c}$

* n is directly proportional to $\frac{1}{\sin\theta_c}$ *

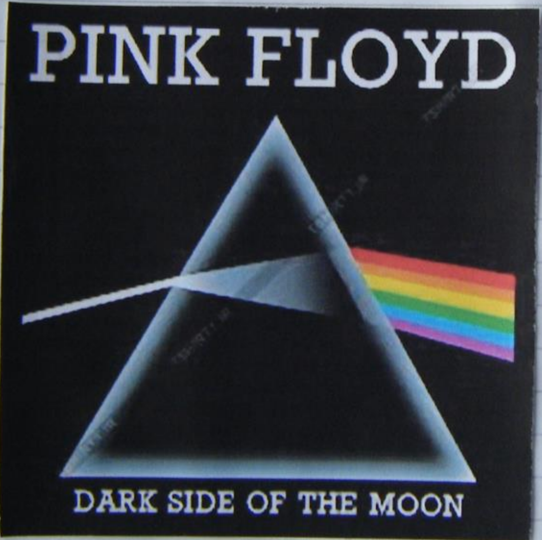
The Visible Spectrum

A triangular prism produces a visible spectrum with white light.

R O Y G B I V

- R — High wavelength, $\lambda \approx 700nm$
- G — $\lambda \approx 550nm$
- V — High frequency, $\lambda \approx 400nm$

Remember Red has a high wavelength.



Pink Floyd are a huge rock band that started in the late 60's.

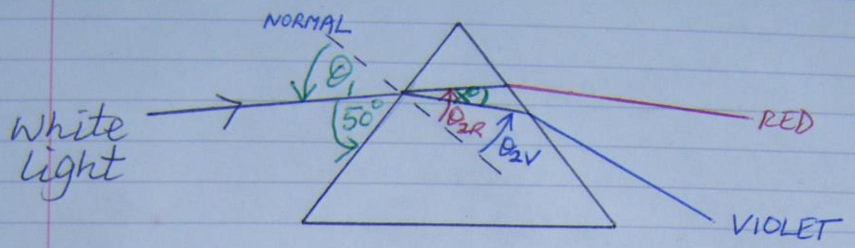
The 'Dark Side of the Moon' album was released in 1973 and it is legendary in rock circles.

This album sleeve is iconic even to this day and it certainly helps the teaching of Physics.

* Other Pink Floyd songs to look out for are:
  - Another Brick in the Wall
  - Run like hell
  - Comfortably numb
  - Shine on you crazy diamond

*

Ex6



n for red light in glass = 1·51
n for violet light in glass = 1·53

Q Calculate or find:

a) Angle in air, θ_1

b) i) Angle of red light in glass, θ_{2R}
ii) Angle of Violet light in glass, θ_{2V}.

c) Angle X° between the red and violet light in glass.

A a) $\theta_1 = 90^\circ - 50^\circ = 40^\circ$

b) $n_R = \dfrac{\sin\theta_1}{\sin\theta_{2R}} \Rightarrow 1{\cdot}51 = \dfrac{\sin 40^\circ}{\sin\theta_{2R}}$

$\Rightarrow \sin\theta_{2R} = \dfrac{\sin 40^\circ}{1{\cdot}51} \Rightarrow \theta_{2R} = \sin^{-1}(0{\cdot}426)$

$\Rightarrow \underline{\theta_{2R} = 25{\cdot}2^\circ}$

($\wedge\wedge \; \dfrac{\sin 40^\circ}{1{\cdot}51} = 0{\cdot}426$ if I have jumped too quickly here!!).

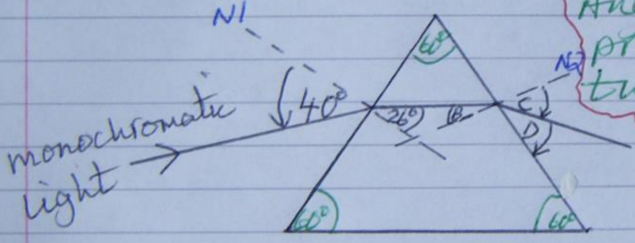
b) ii) $n_V = \frac{\sin\theta_1}{\sin\theta_{2V}} \Rightarrow 1.53 = \frac{\sin 40^\circ}{\sin\theta_{2V}}$

$\Rightarrow \sin\theta_{2V} = \frac{\sin 40^\circ}{1.53} = 0.420$

$\Rightarrow \theta_{2V} = \sin^{-1}(0.420) = \underline{24.8^\circ}$

c) $X^\circ = \theta_{2R} - \theta_{2V} = 25.2^\circ - 24.8^\circ = \underline{0.4^\circ}$

EX 7



Angles inside the prism between the two normals add up to 60°.
ie $26° + B° = 60°$

Q Calculate or find:

a) Refractive index n of the prism material.

b) Angle D

c) If the refractive index n is increased to 1.55 then redraw the ray of light through the prism with θ_1 staying at 40°.

4 a) $n = \frac{\sin\theta_1}{\sin\theta_2} = \frac{\sin 40^\circ}{\sin 26^\circ} = \underline{1.47}$

b) $26^\circ + B^\circ = 60^\circ \quad \therefore \quad \underline{B = 34^\circ}$

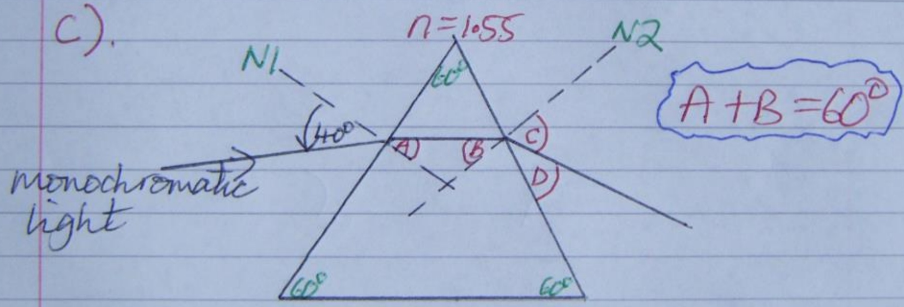
$n = \frac{\sin\theta_1}{\sin\theta_2} \Rightarrow 1.47 = \frac{\sin C^\circ}{\sin 34^\circ}$

$\Rightarrow \sin C^\circ = 1.47 \times \sin 34^\circ = 0.822$

$\Rightarrow C = \sin^{-1}(0.822) = \underline{55.3^\circ}$

$\therefore \quad D = 90^\circ - 55.3^\circ = \underline{34.7^\circ}$

c).



$\underline{A^\circ} \Rightarrow n = \frac{\sin\theta_1}{\sin\theta_2} \Rightarrow 1.55 = \frac{\sin 40^\circ}{\sin A^\circ}$

$\Rightarrow \sin A^\circ = \frac{\sin 40^\circ}{1.55} = 0.415$

$\Rightarrow A^\circ = \sin^{-1}(0.415) = \underline{24.5^\circ}$

$\underline{\underline{B^\circ}} \Rightarrow A^\circ + B^\circ = 60^\circ \Rightarrow 24.5^\circ + B^\circ = 60^\circ$

$\Rightarrow B^\circ = 60^\circ - 24.5^\circ = \underline{\underline{35.5^\circ}}$

$\underline{\underline{C^\circ}} \Rightarrow n = \dfrac{\sin C^\circ}{\sin B^\circ} \Rightarrow 1.55 = \dfrac{\sin C^\circ}{\sin 35.5^\circ}$

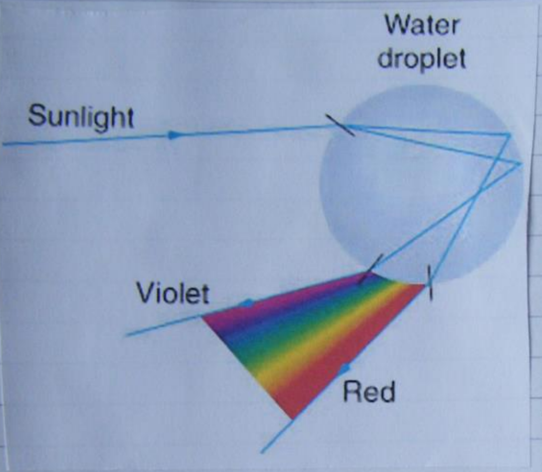
$\Rightarrow \sin C^\circ = 1.55 \times \sin 35.5^\circ = 0.900$

$\Rightarrow C^\circ = \sin^{-1}(0.900) = \underline{\underline{64.2^\circ}}$

$\underline{\underline{D^\circ}} \Rightarrow D^\circ = 90^\circ - 64.2^\circ = \underline{\underline{25.8^\circ}}$

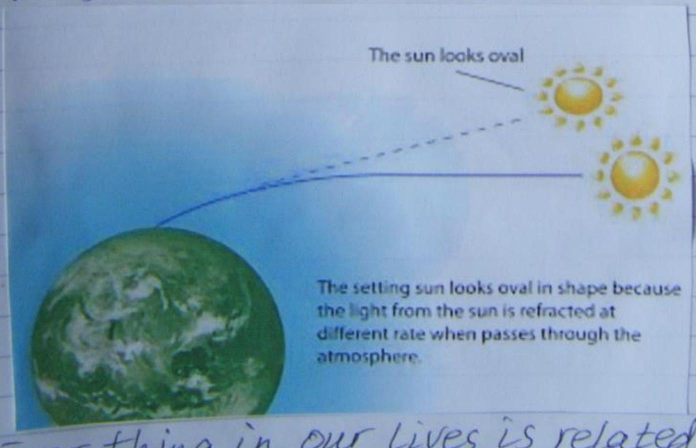
Everyday applications of refraction.

1) Sunlight (White light) through a water droplet



Refraction of the white sunlight takes place when passing from air into water.
The frequencies of the white light then spread out and then undergo T.I.R.
The order of the colours in the visible spectrum then reverse and this is clearly seen when they come back out into the air ie VIBGYOR.

2) Why the sun looks oval in shape at sunset.

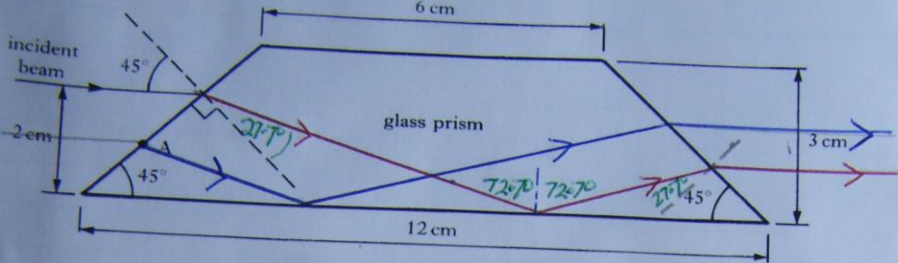


Everything in our Lives is related to Physics!! (Even going to the toilet!!)

Ex8 (1992 Past Paper 2 Q10)

Q

A pupil finds a glass prism of the shape shown below when she dismantles an old optical instrument.



To investigate the optical properties of the prism, she directs a narrow beam of red light towards the prism as shown.

The glass prism has a refractive index of 1·52 for this red light.

(*a*) (i) Calculate the value of the critical angle for this light in the glass prism.

(ii) On the square-ruled paper provided, draw the prism with the dimensions stated in the diagram.

On your diagram, show the passage of the light beam until after it emerges from the prism.

Mark on your diagram the values of all relevant angles.

(iii) A second beam of light, parallel to the first and of the same wavelength, is now directed onto the prism at A.

Add to your diagram the complete path of this beam through the prism. **7**

(*b*) How would a distant object appear when viewed through the prism when it is held as shown below?

A

a) i) $n = \frac{1}{\sin\theta_c} \Rightarrow \sin\theta_c = \frac{1}{n} = \frac{1}{1.52}$

$\Rightarrow \sin\theta_c = 0.658 \Rightarrow \theta_c = \sin^{-1}(0.658) = \underline{41.1^\circ}$

a) ii) + iii) $n = \frac{\sin\theta_1}{\sin\theta_2} \Rightarrow 1.52 = \frac{\sin 45^\circ}{\sin\theta_2}$

$\Rightarrow \sin\theta_2 = \frac{\sin 45^\circ}{1.52} = 0.465$

$\Rightarrow \theta_2 = \sin^{-1}(0.465) = \underline{\underline{27.7^\circ}}$

When the ray of light enters the glass prism it refracts and bends towards the normal (ie from 45° to 27.7°). When the ray reaches the bottom of the prism it will hit it at 45° + 27.7° = 72.7°

72.7° > 41.1° ie the critical angle for the glass

∴ The light will Totally Internally Reflect (T.I.R) off the bottom side.

On reflection the ray will then hit the far away side at 27.7°.

The light will then leave the prism at 45°.

ie $n = \frac{\sin\theta_1}{\sin\theta_2}$ for entering and leaving the prism where $\theta_1 = 45^\circ$ and $\theta_2 = 27.7^\circ$.

$\Uparrow$ In air $\qquad \Uparrow$ In glass.

b) The image would be Inverted.