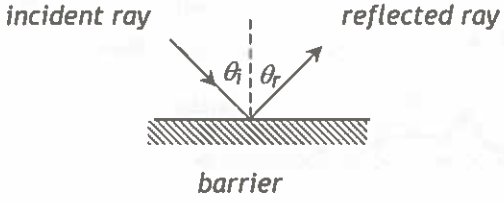
# 5.3 Summary Notes – Reflection & Refraction

Light obeys the **law of reflection:** $\theta_i = \theta_r$.




**Refraction** is the changing of direction or bending of a ray as it passes from one medium to another. It is caused by a sudden change in speed as the waves pass from one medium to another.

Snell's Law

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

Where:

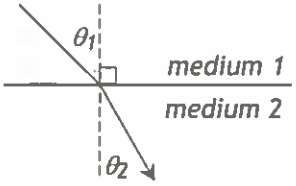
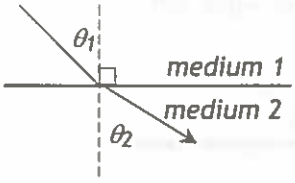
- $n_1$ is the refractive index of the medium where the incidence ray comes from (no units)
- $n_2$ is the refractive index of the medium where the refractive ray exists (no units)
- $\theta_1$ is the angle of incidence (degrees)
- $\theta_2$ is the refracted angle (degrees)

Notes:

monochromatic light
- 1 light
- 1 wavelength

-use Snell's Law.

**N.B.,** frequency will not change.

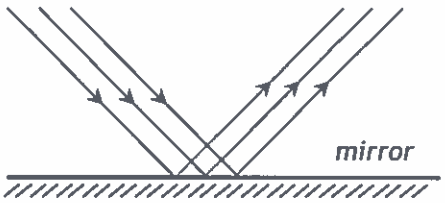
| Speed decreases | Speed increases |
|---|---|
| • Bends towards the normal $\theta_2 < \theta_1$<br>• Wave is faster in medium 1<br>• Refractive index of 1 is less than 2 | • Bends away from the normal $\theta_2 > \theta_1$<br>• Wave is slower in medium 1<br>• Refractive index of 1 is greater than 2 |
|  |  |

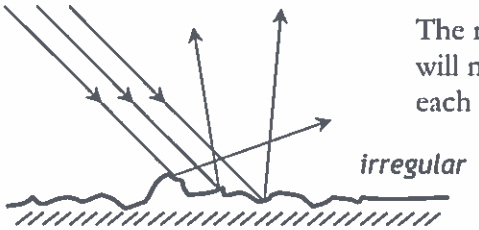


**Critical angle is** the angle of the incident ray that causes the refracted ray to be 90° relative to the normal line. When the incident ray is at an angle greater than the critical angle, total internal reflection occurs. This can only occur when light goes from a high index of refraction to a low index of refraction.

## Examples

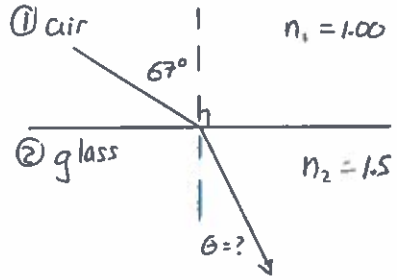
1. A wave contacts two surfaces as shown below. Draw the reflected wave off of each surface.




The reflected waves will not be parallel to each other.

2. A ray of light from air strikes the surface of a block of glass, having a refractive index of 1.50, at an angle of 67°. Determine the angle of refraction. (The refractive index of air is on your data sheet.)




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

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

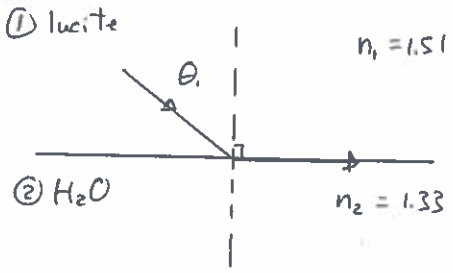
$$= \frac{(1)\sin 67°}{1.5}$$

$$\theta_2 = 37.855$$

The angle of refraction is 38°.

total internal reflection

3. Lucite is a strong clear plastic used for many windows. Determine the critical angle for a water-lucite system if the refractive index of water is 1.33 and 1.51 for Lucite.




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

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

$$= \frac{(1.33)\sin 90°}{1.51}$$

$$\theta_1 = 61.738°$$

The critical angle is 61.7°.

## Problems

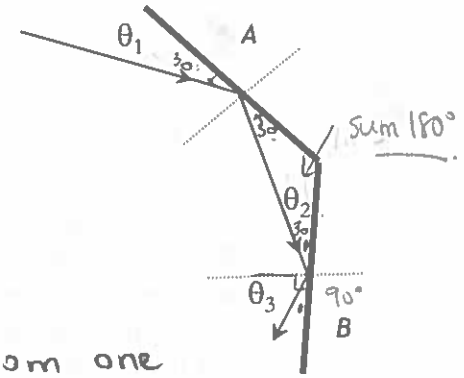
1. If the angle of reflection from a mirror is 35.0°, determine the angle of incidence. [Appendix A]

The angle of incidence is 35°

$\theta_R = \theta_I$

2. A light ray is reflected of a system of two mirrors as shown in the diagram. If the angle between the surface of mirror A and mirror B is 120°, complete the chart for the angle $\theta_2$ and $\theta_3$. [Appendix A]

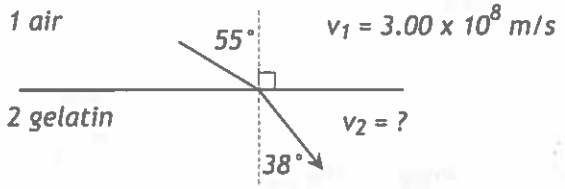
| $\theta_1$ (degrees) | $\theta_2$ (degrees) | $\theta_3$ (degrees) |
|---|---|---|
| 30 | 30° | 60° |
| 40 | 20° | 70° |
| 50 | 10° | 80° |




3. Define refraction. [Appendix A]

The bending of a wave as it passes from one medium into another medium.

4. A student sets up a system where laser light is travelling from air and strikes a block of clear gelatin as shown in the diagram below. Determine the speed of light in the gelatin. [2.3 x $10^8$ m/s]



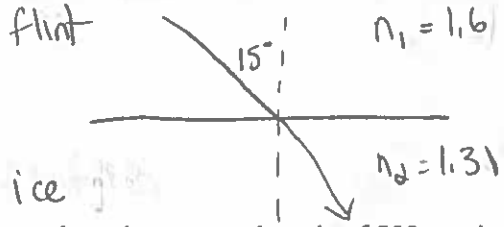

$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$

$v_2 = \frac{v_1 \sin\theta_2}{\sin\theta_1} = \frac{3\times10^8 \sin 38^\circ}{\sin 55^\circ}$

$= 2.25\times10^8$ m/s

$n = 1.31$ $n = 1.60$

5. A layer of ice is next to a piece of flint glass. A ray of light in the flint enters the ice at an angle of 15.0°. Determine the angle of refraction in ice. (Use your data sheet in Appendix C, page 377 for index of refractions.) [18.4°]



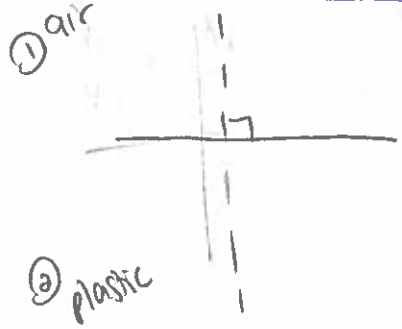

$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$

$\frac{\sin 15^\circ}{\sin\theta_2} = \frac{1.31}{1.6}$

$\sin\theta_2 = 0.316$

$\theta = 18.4^\circ$

6. A green laser has a wavelength of 532 nm in air and is 50 times brighter than the more common red lasers. Determine the speed of the 532 nm laser light in a transparent plastic if its refracted wavelength is 480 nm in the plastic. [2.71 x $10^8$ m/s]




$n = 1$

$\lambda_1 = 532\text{nm} = 532\times10^{-7}$ m

$v = 3\times10^8$

$\lambda_1 = 480\times10^{-7}$

$v = ?$

$g_{laser} = 532\times10^{-9}$

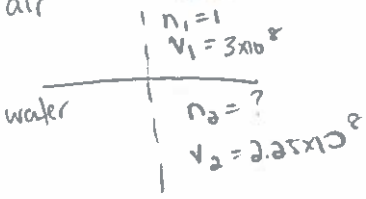
$_{plastic}\ 480\times10^{-3}$

$\frac{v_2}{v_1} = \frac{\lambda_2}{\lambda_1}$

$v_2 = \frac{\lambda_2 v_1}{\lambda_1} = \frac{480\times10^{-7}(3\times10^8)}{532\times10^{-7}}$

$v_2 = 2.71\times10^8$ m/s

7. Light travelling from air enters a layer of water. The speed of light through water is 2.25 x $10^8$ m/s. Calculate the water's index of refraction relative to air. [1.33]

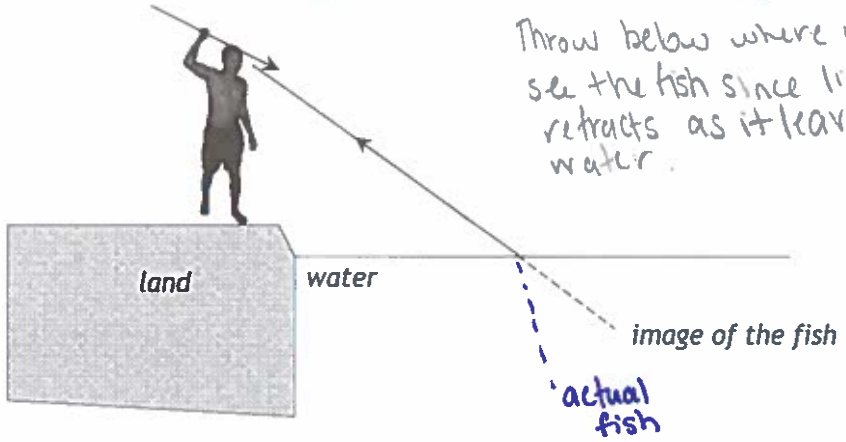



$\frac{n_2}{n_1} = \frac{v_1}{v_2}$

$n_2 = \frac{n_1 v_1}{v_2} = \frac{1(3 \times 10^8)}{2.25 \times 10^8}$

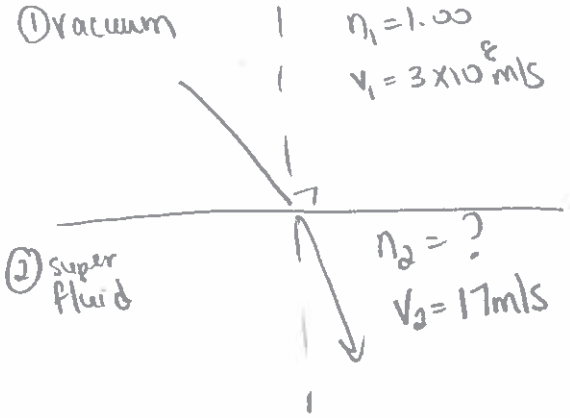
$n_2 = 1.33$

8. Inuit, along with many other Native Americans, have long used spear fishing for gathering food. Spear fishing not only requires skill in throwing a spear but also knowledge of the phenomenon of refraction. Consider the diagram below. The spear-fisher sees an image of the fish represented in the diagram below. Should the spear fisher throw the spear where he sees the fish to be? Explain using the diagram below. [Appendix A]




Throw below where you see the fish since light refracts as it leaves water.

9. A Bose-Einstein condensate is a gaseous superfluid near absolute zero. It was used in 1999 to slow light to a speed of 17 m/s. Calculate the refractive index of this substance. [1.8 x $10^7$]




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

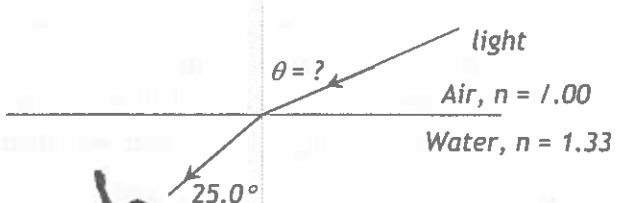
$n_2 = \frac{n_1 v_1}{v_2}$

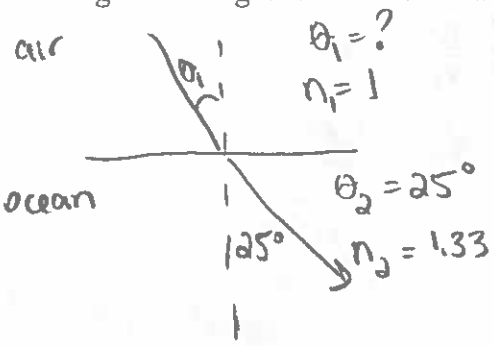
$= \frac{1(3 \times 10^8)}{17}$

$= 17647059$

The refractive index of the Bose-Einstein condensate is $1.8 \times 10^7$

10. A swimmer (while underwater) views rays of light entering the ocean water from the air at a refracted angle of 25.0°. Calculate the incident angle of the light as it enters the water. [34.2°]




$\theta_1 = ?$ $n_1 = 1$ $\theta_2 = 25°$ $n_2 = 1.33$

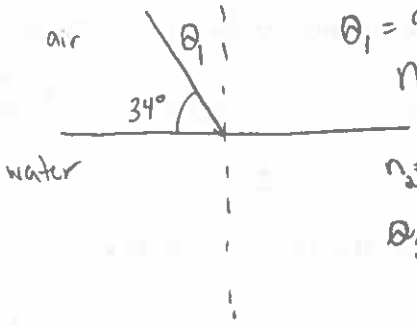
$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$ $\sin\theta_1 = \frac{n_2 \sin\theta_2}{n_1}$

$\sin\theta_1 = \frac{1.33 \sin 25°}{1}$

$= 0.56208$

$= 34.2°$

11. Light from air strikes the surface of water (n = 1.33) at an angle of 34° relative to the surface as it comes from the air. Calculate the angle of refraction. [39°]




$\theta_1 = 90 - 34 = 56°$ $n_1 = 1$ $n_2 = 1.33$ $\theta_2 = ?$

$\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$ $\sin\theta_2 = 0.62334$

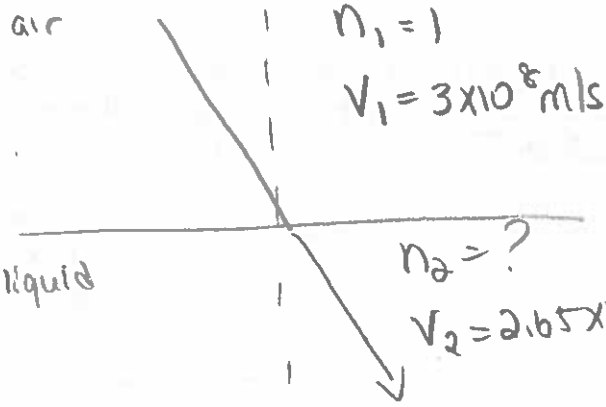
$= 38.56$

$= 39°$

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

$= \frac{1 \sin 56°}{1.33}$

12. A beam of light travels from air to a liquid in which the speed of light is $2.65 \times 10^8$ m/s. Determine the index of refraction of the liquid. [1.13]




$n_1 = 1$ $V_1 = 3 \times 10^8$ m/s $n_2 = ?$ $V_2 = 2.65 \times 10^8$ m/s

$\frac{n_2}{n_1} = \frac{V_1}{V_2}$

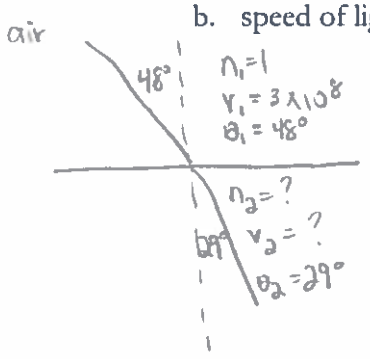
$n_2 = \frac{n_1 V_1}{V_2}$

$= \frac{1 \cdot 3 \times 10^8}{2.65 \times 10^8}$

$= 1.132$

$= 1.13$

13. Green laser light travels from air into an unknown material. If the angle between the beam and the normal is 48.0° in air and 29.0° in the unknown material, determine the
    a. index of refraction of the unknown material. [1.53]
    b. speed of light in the unknown material. [1.96 x $10^8$ m/s]




a) $\frac{\sin\theta_1}{\sin\theta_2} = \frac{n_2}{n_1}$

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

$= \frac{1 \sin 48°}{\sin 29°}$

$n_2 = 1.53$

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

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

$= \frac{3 \times 10^8 \cdot 1}{1.5329}$

$= 1.957 \times 10^8 = 1.96 \times 10^8$ m/s

*Use the information below to answer questions 14 – 16.*

The index of refraction of a substance may be defined as the ratio of the speed of light in a vacuum to the speed of light through the substance.

→ still use snell's law because n in vacuum is 1

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

14. Determine the refractive index of a substance where light travels at 2.45 x $10^8$ m/s. [1.22]

$v = 2.45 \times 10^8$

$n = ?$

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

$n = \frac{3 \times 10^8}{2.45 \times 10^8}$

$n = 1.22$

15. The Northwest Territories has three large diamond mines near Yellowknife. Diamonds may be cleaned in ethanol. The refractive index of ethanol is 1.36 and 2.42 for diamond. Calculate the difference in the speed for light travelling through ethanol into a diamond. [9.66 x $10^7$ m/s]

ethanol

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

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

$= \frac{3 \times 10^8}{1.36}$

$v = 2.206 \times 10^8$ m/s

diamond

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

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

$= \frac{3 \times 10^8}{2.42}$

$v = 1.2397 \times 10^8$ m/s

$\Delta v = 2.206 \times 10^8 - 1.239 \times 10^8$

$9.6622 \times 10^7$ m/s

$= 9.66 \times 10^7$ m/s

16. State the relationship between the index of refraction of a material and the speed of light. [Appendix A]

As the index of refraction increases, the speed of light decreases relative to the speed of light in a vacuum (more dense → slower waves)

17. Monochromatic light travels from air to water. Describe what happens to the light wave's
    a. speed. [Appendix A]
    b. wavelength. [Appendix A]
    c. frequency. [Appendix A]

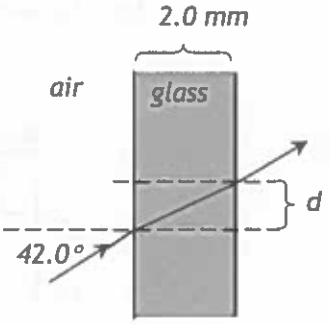
less dense to more dense

a) speed decreases

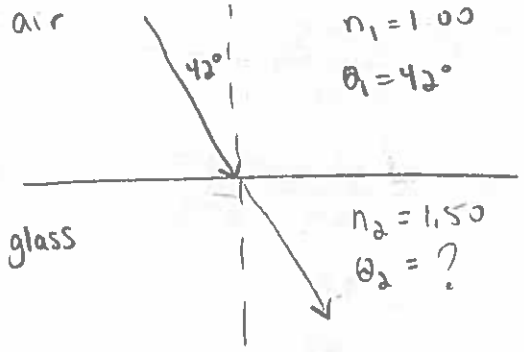
b) wavelength decreases

c) frequency stays the same.

18. The diagram on the right represents light travelling through a glass windowpane. The index of refraction of the glass is 1.50 and it is 2.0 mm thick. Determine the
    a. angle of refraction in the glass. [26.5°]
    b. distance "d". [1.0 mm]




a)




$n_1 = 1.00$

$\theta_1 = 42°$

$n_2 = 1.50$

$\theta_2 = ?$

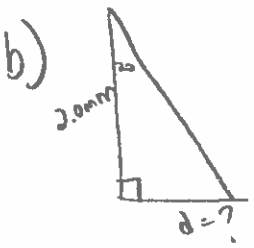
$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{n_1}{n_2}$$

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

$$= \frac{1 \sin 42}{1.5}$$

$$\theta_2 = 26.5°$$

b)




$$\tan\theta = \frac{O}{A}$$

$$\tan 26.5 = \frac{d}{2}$$

$$2 \tan 26.5 = d$$

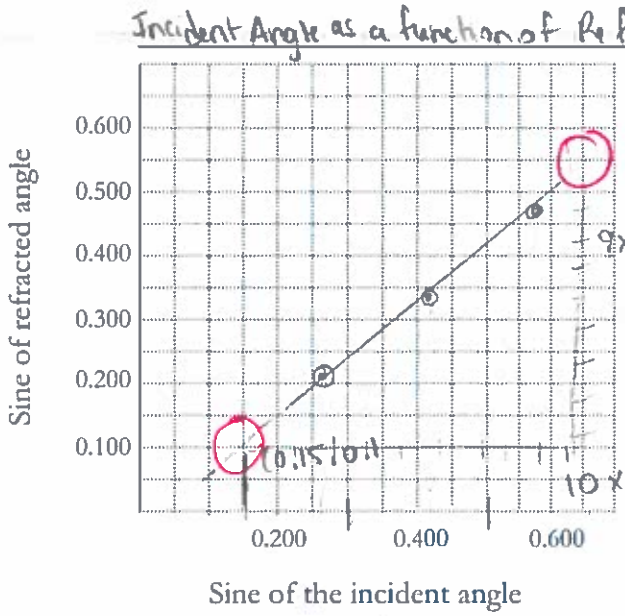
$$d = 0.997$$

$$d = 1.0\text{mm}$$

19. Aidan sets out to determine the speed of light in a viscous fluid by using the principles of refraction. Using a red pen laser he manipulates the angle of incidence and records the angle of refraction.

| Incident angle (degrees) | Sine of incident angle | Refracted angle (degrees) | Sine of refracted angle |
|---|---|---|---|
| 15.0 | sin15 = 0.259 | 12.0 | sin12 = 0.208 |
| 25.0 | sin25 = 0.423 | 20.0 | sin20 = 0.342 |
| 35.0 | sin35 = 0.574 | 28.0 | sin28 = 0.469 |
| 45.0 | sin45 = 0.707 | 36.0 | sin36 = 0.588 |

a. Determine the sine of the angles and place data in the chart.
b. Plot the sine of the angles.
c. Determine the slope of the line. [~0.864]
d. Use the slope to determine the speed of light in the viscous fluid. [~2.59 x $10^8$ m/s]




$\text{slope} = \frac{\Delta y}{\Delta x} = \frac{y_2 - y}{x_2 - x}$

$\text{slope} = \frac{0.588 - 0.208}{0.707 - 0.259} = \frac{0.38}{0.448}$

slope = 0.848

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

$\text{slope} = \frac{\Delta \sin\theta_2}{\Delta \sin\theta_1}$ so $\text{slope} = \frac{v_2}{v_1}$

$\text{slope} = \frac{v_2}{v_1}$

$v_2 = v_1 \cdot \text{slope}$

$= 3 \times 10^8 \cdot 0.848$

$= 2.54 \times 10^8$ m/s

responding = slope + manipulated

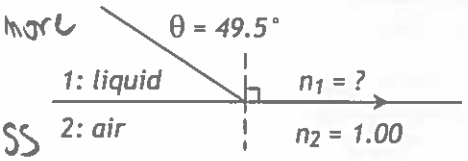
↳ estimated

critical angle

* must be more to less *

$\theta_2 = 90°$ for all critical angle questions

20. A critical angle may occur if a waves travels from a substance having a high refractive index to a substance with low refractive index. The critical angle for a given liquid-air system is 49.5°. Calculate the refractive index of the liquid. [1.32]




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

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

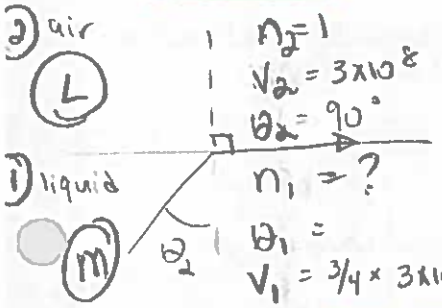
$= \frac{1 \sin 90°}{\sin 49.5°}$

$= 1.3151$

$n = 1.32$

21. The speed of light in a clear liquid is three-quarters the speed of light in air. Determine the critical angle of the liquid. [48.6°]

$\theta_1 = 90°$

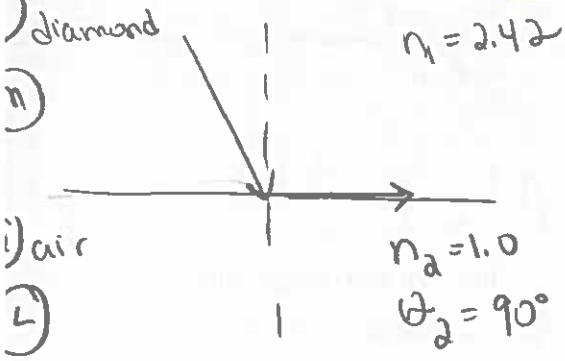



$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$ $\sin\theta_1 = \frac{v_1 \sin\theta_2}{v_2}$

$= \frac{2.25 \times 10^8 \sin 90°}{3 \times 10^8}$

$= 48.59°$ $= 48.6°$

22. Determine the critical angle for a diamond/air system. [24.4°]




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

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

$= \frac{1 \sin 90°}{2.42}$

$= 24.41 = 24.4°$

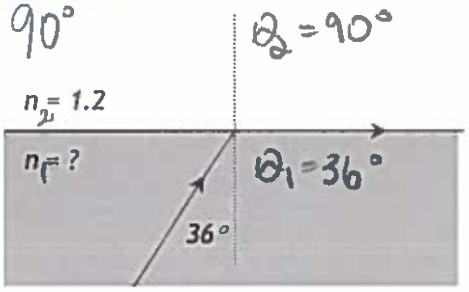
23. Describe what will happen when the angle of the incident ray is greater than the critical angle. [Appendix A]

Total internal reflection will occur.

→ the light reflects & stays in the diamond & causes it to "sparkle"

$\theta_2 = 90°$ always.

24. A monochromatic light ray is incident on the interface between two substances at the critical angle as shown in the diagram below. Determine the missing index of refraction. [2.0]




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

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

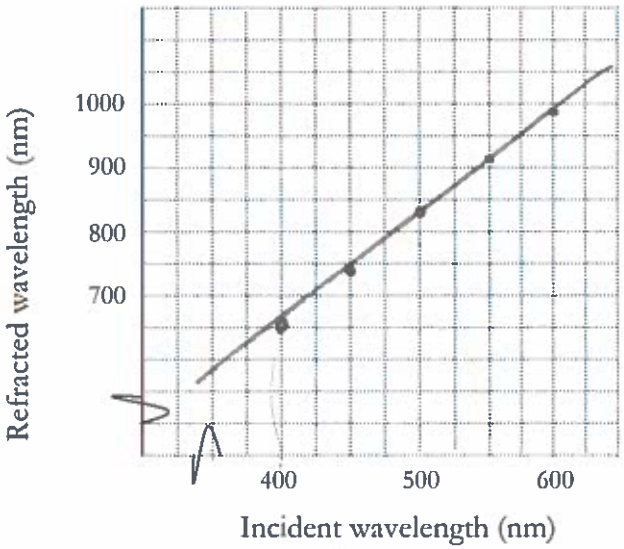
$$= \frac{1.2 \sin 90°}{\sin 36°}$$

$$= 2.041 = \boxed{2.0}$$

25. A researcher created an experiment to determine the critical angle of an unknown substance using a variable wavelength light emitter and detector. The angle of incident is held constant.

| Incident wavelength (nm) | Refracted wavelength (nm) |
|---|---|
| 400 | 665 |
| 450 | 747 |
| 500 | 830 |
| 550 | 913 |
| 600 | 996 |

Refracted Wavelength as a Function of Incident Wavelength




$y = 1.656x + 2.2$

a. Plot the information.
b. Determine the slope of the line. [~1.62]
c. Use the slope to determine the critical angle. [~38.1°]

$$\text{slope} = \frac{y_2 - y_1}{x_2 - x_1} = \frac{996 - 665}{600 - 400}$$

$$= \frac{331}{200}$$

$$= 1.655$$

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{\lambda_1}{\lambda_2}$$

responding = slope + manipulated

$$\therefore \text{slope} = \frac{\sin\theta_2}{\sin\theta_1}$$

$$\sin\theta_1 = \frac{\sin\theta_2}{\text{slope}} = \frac{\sin 90°}{1.62}$$

$$\theta_1 = \boxed{38.1°}$$