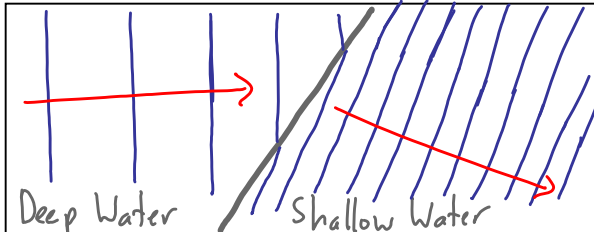


Unit 8: Waves

4 – Refraction

Wave speed depends on the media. What happens when waves travel from one medium into another?

Consider some waves moving from the open ocean to shore. As the water gets more and more shallow, the waves slow down (velocity decreases).



Waves traveling perpendicular to the new medium ($\theta_i = 0^\circ$) continue in the same direction.

- Velocity changes, but frequency stays constant
- Therefore wavelength also changes

When waves are not perpendicular they will also bend.

Refraction: bending of light as it changes media

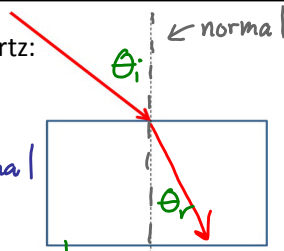
Optical density: a measure of how difficult it is for light to travel in a substance

(vacuum < air < water < glass < diamond)

Consider a laser shining into a piece of quartz:

Angle of Incidence: angle between incident ray and normal

Angle of Refraction: angle between refracted ray and normal



Snell's law

$$n_i \sin \theta_i = n_r \sin \theta_r$$

n = index of refraction

θ_i = angle of incidence

θ_r = angle of refraction

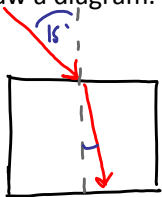
When light travels from:

- **less dense to more dense** it slows down and bends towards the normal
- **more dense to less dense** medium it speeds up and bend away from the normal.

Medium	n	Medium	n
Vacuum	1	Crown glass	1.52
Air	1.0003	Quartz	1.54
Water	1.33	Flint Glass	1.61
Ethanol	1.36	Diamond	2.42

Ex: A ray of light traveling in air strikes a block of quartz at a angle of 15° . Find the angle of refraction.

Draw a diagram.



$$n_i \sin \theta_i = n_r \sin \theta_r$$

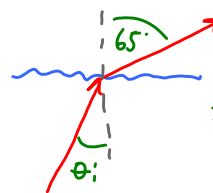
$$\sin \theta_r = \frac{n_i \sin \theta_i}{n_r} = \frac{1.0003 \sin 15^\circ}{1.54}$$

$$= 0.1681$$

$$\theta_r = \sin^{-1}(0.1681) = \boxed{9.7^\circ}$$

Ex: A ray of light travels from underwater into air. It travels in the air at an angle of 65° , find the incident angle.

Draw a diagram.



$$\sin \theta_i = \frac{n_r \sin \theta_r}{n_i}$$

$$= \frac{1.0003 \sin 65^\circ}{1.33} = 0.6816$$

$$\theta_i = \sin^{-1}(0.6816) = \boxed{43^\circ}$$

The index of refraction for any substance is:

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

Where:

n = index of refraction

c = speed of light in a vacuum

v = speed of light in the substance

Ex: What is the speed of light in water?

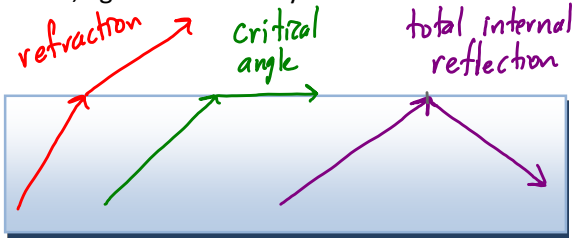
$$n = \frac{c}{v}$$

$$v = \frac{c}{n} = \frac{3.00 \times 10^8 \text{ m/s}}{1.33}$$

$$= \boxed{2.26 \times 10^8 \text{ m/s}}$$

Total Internal Reflection

When passing from a more dense to a less dense medium, light refracts away from the normal.



If the angle is large enough then the angle of refraction will be parallel to the medium boundary. (i.e. $\theta_r = 90^\circ$)

Critical angle: θ_c ; that results in $\theta_r = 90^\circ$

Total Internal Reflection: occurs when $\theta_i > \theta_c$

Ex: Find the critical angle for light traveling from water into air.

Draw a diagram.

Diagram: A horizontal boundary separates water (bottom) from air (top). A red ray is incident from the water at an angle θ_c to the normal. The refracted ray in the air is shown as a red arrow pointing along the boundary (90 degrees).

$$n_i \sin \theta_c = n_r \sin \theta_r$$

$$\sin \theta_c = \frac{n_r \sin \theta_r}{n_i} = \frac{1.0003 \sin 90^\circ}{1.33}$$

$$\sin \theta_c = 0.7521 \quad \theta_c = 48.8^\circ$$

Snell's Law

1) Light travels at 2.62×10^8 m/s in a new clear type of plastic. What is this new product's index of refraction?

2) How fast does light travel in zircon ($n = 1.92$)?

3) Light traveling in air hits a diamond surface at 42° to the normal. To what angle is it refracted in the diamond?

4) Light leaves a ruby and enters water. If the angle of refraction is 60° , what was the incident angle inside the ruby? The index of refraction for ruby is 1.55.

5) An experiment is done with an unknown substance. Light entering the substance from air at 38° to the normal is refracted to 23.6° . What is the sample's index of refraction? What might the sample be made of? How fast does light travel in the sample?

6) What is the critical angle for light leaving zircon and entering glass of the flint variety?

7) What is the critical angle for light leaving diamond and entering air?

8) A killer whale in its pool observes total internal reflection when it looks at the glass wall at a certain angle (it sees the reflection of the pool, and things in it). At what boundary does this reflection occur, water to glass or glass to air?

1) 1.15 2) 1.56×10^8 m/s 3) 16° 4) 48° 5) 1.54, quartz, 1.95×10^8 m/s 6) 59° 7) 24° 8) Glass to air