Lesson 27: Refraction

Illustration 1: Refraction makes the pen look bent.

Refraction is when waves change the direction they are traveling when they go from one medium to another.

- Have you ever looked at something like a pencil or pen sitting in a cup of water? It probably looked something like *Illustration 1*.
  - Notice how the pen looks like it is bent and bigger in the water… something must be happening to the visible light as it travels through two different substances… water and air.
  - If someone is standing in a swimming pool, the light traveling through the water from the person's feet does the same thing as it changes medium and travels into the air. This bending often makes it look like a person is short in the water.
- The way the waves move changes by moving to a different medium.

Since Ptolemy's time (about 100AD) people knew about refraction, but they didn't know why it happened, or how to predict and calculate it.

- In the year 1600 a Dutch mathematician named Willebrord Snell was playing around with numbers and figured out a formula that fit what everyone was measuring in their labs.
  - This meant that Snell had a mathematical formula that fit the empirical evidence collected in labs.
- The **Law of Refraction** (AKA "**Snell's Law**") in its basic form allows us to do calculations of how a beam will bend when it moves from one medium to another. In its full form, it also lets you do calculations involving wavelength and velocity of EMR in different media.

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

θ = angle measured from normal
n = **index of refraction** for medium
λ = wavelength of light
v = velocity of light

The plural form of **index** is **indices**.

The **index of refraction** (n) is a way of comparing the *optical density* of different materials.

- Think of optical density as a measurement of how easily light can travel through the medium.
  - A low index of refraction (like water $n_w = 1.33$) is pretty easy to travel through.
  - A high index (like diamond $n_d = 2.42$) is difficult for light to travel through.
- The index of a medium is usually measured in an actual experiment… there's no reliable way to just predict what they will be.
- Index of refraction has no units and is based on a comparison to how light travels in a vacuum.
- The following table gives you an idea of some of the values of index of refraction for some media.
  - You do not have to memorize this table.

Medium	Index
Vacuum	1.00
Air †	1.0003
Water	1.33
Ethanol	1.36
Glycerin	1.47
Crown Glass ‡	1.50 – 1.62
Quartz	1.54
Flint Glass ‡	1.45 – 2.00
Diamond	2.42

† Simply use 1.00 in calculations.
‡ Varies slightly due to inconsistencies in the glass and different methods of manufacturing.

Example 1: A beam of light traveling in glycerin hits the boundary between itself and water at an angle of 43° from the normal. **Determine** the angle of refraction through the water.

We can call the original beam traveling in the glycerin the incident ray, and the light traveling in the water the refracted ray. The indices for glycerin and water are on the table above, and then we use Snell's Law to figure out the angle.

We can call either of media "one" and the other "two," as long as we stay consistent. For this question we're going to say water is one and glycerin is two, and that way we don't have to do as much cross multiplying in the formula.

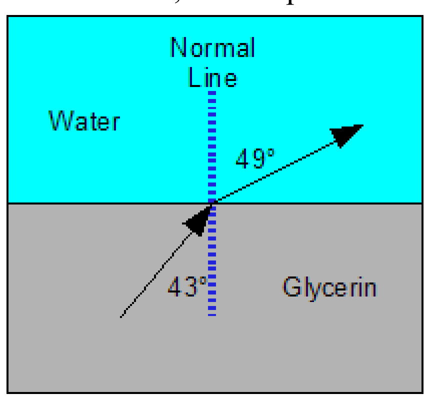
In the formula we only use the terms that we need, and drop the others.

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

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

$$\sin\theta_1=\frac{\sin 43^o(1.47)}{1.33}$$

$$\theta_1=48.9196=49^o$$



If you didn't get the right answer...

1. Is your calculator in degree mode?
2. Did you enter sin 43° in your calculator correctly so that you only took the sin of that angle?
3. Did you take the inverse sin at the very end to get the angle?

We will usually be describing refraction in terms of whether the beam of light bends away from or towards the normal.

- Going from more dense to less dense = bend away
- Going from less dense to more dense = bend towards

Speed of Light

Notice in Snell's Law that the velocity of light will change in different media.

- The speed of light is a constant in one particular medium.
- The speed that we use as a benchmark at all times is the speed of light in vacuum, 3.00e8m/s.

Scientists have successfully slowed light down to about 1 km/h! Although this is tough to do, it is possible.

- It is even possible for light to go faster if it is in a medium with an index of refraction less than 1.0.
- This does not break Einstein's rules about the speed of light being the fastest speed.
  - He said no thing (with mass) can go faster than 3.00e8m/s… light doesn't have mass!
  - And, in a particular medium, the speed of light is still the fastest possible speed.

Using the speed of light in a particular medium is actually one of the best ways to measure the index of refraction for that medium.

- The light first travels through vacuum and then enters the other medium where its new speed is measured. From that you can calculate the index of refraction.

Example 3: A student is doing a lab. They test a material that light travels at 2.21e8m/s through. **Determine** what substance this might be.

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

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

$$n_2=\frac{1.00(3.00e8)}{2.21e8}$$

$$n_2=1.35747=1.36$$

From the chart we see that ethanol has an index of refraction of 1.36. There might be other substances with this same index, so we can't be sure.

Using Snell's Law to Predict Changes in Wavelength

You don't usually observe color changes, since you need to actually be in the other medium to be able to see the different wavelength.

- This follows from the change in the speed of light.
  - Remember that in Physics 20 we learned that as a wave travels from one medium to another, its frequency remains constant.
  - According to $v = f\lambda$, if $\boldsymbol{v}$ changes but $\boldsymbol{f}$ stays the same, $\boldsymbol{\lambda}$ must change.

Example 2: A beam of red light (λ = 700nm) is traveling through water (n = 1.33). If it leaves the water and travels into a piece of flint glass (n = 1.75), determine the color (approximately) that it will be.

$$\frac{n_2}{n_1}=\frac{\lambda_1}{\lambda_2}$$

$$\lambda_1=\frac{\lambda_2 n_2}{n_1}$$

$$\lambda_1=\frac{700\text{e-}9(1.33)}{1.75}$$

$$\lambda_1=5.32\text{e-}7\,m=532\text{e-}9=532\,nm$$

This makes it a greenish color, maybe yellowish–green.

Homework

p668 #1-3
p670 #1