# 3.4: Refraction

## Tutorial 3.4: Refraction

When waves pass from one medium to another they often interact with the medium and change their wavelength. This means their speed also changes. Electromagnetic waves may be briefly absorbed by the atoms of substance (depending on the wavelength of and the type of atom) so that the total time taken to traverse the material is longer than if the wave were in free space, even though they travel at the usual speed of light between atoms.

A wave that changes speed as it crosses the boundary of between two materials will also change direction if it crosses the boundary at an angle other than perpendicular. This is because the part of the wavefront that gets to the boundary first slows down first. The bending of a wave due to changes in speed as it crosses a boundary is called **refraction**.

The ratio of the speed of light in a material to the speed in a vacuum ($c = 3.0 \times 10^9 \text{ m/s}$) is called the index of refraction; $n = c/v$ where $v$ is the speed of light in the medium. In this simulation we will investigate the effects of a change in the speed of a wave as it moves from one material to another. Although our example is for light, the same behavior can be demonstrated with other waves. For example, much of what we know about the interior of the earth, the sun and other planets comes from tracking earthquake waves when they refract as they pass through layers of material that have different densities.

The relationship between the index of refraction and the change in the direction angle of the a ray as it goes across a medium is given by **Snell's law**: $n_1 \sin\theta_1 = n_2 \sin\theta_2$ where $n_1$ and $\theta_1$ are values measured on side of the boundary and the subscript $2$ is for the material on the other side of the boundary.

## Refraction

### Questions:

The simulation shows a ray of light passing through a medium with index of refraction n surrounded by air on both sides. You can move the protractor around and use it to measure angles by dragging the tip of the arrow.

**Exercise 3.4.1**

Set the index of refraction to $1.40$. Change the angle of the rays from the source. The **angle of incidence** $\theta$ is the angle the ray makes with a perpendicular to the surface (not the angle between the ray and the surface). Use the protractor to measure the angle of incidence (put the bottom left edge of the protractor where the ray enters the glass and use the slider to line up the arrow with the ray). Move the protractor to the boundary and line up the arrow with the rays inside the material to get the **refracted angle** (the angle inside the medium).

**Exercise 3.4.2**

The index of refraction of air is approximately one (light travels about as fast in air as it does in a vacume). Use Snell's law to calculate the index of refraction in the medium. ($n_1 = 1$; $\theta_1 =$ the incident angle; $\theta_2$ is the refracted angle; you are solving for $n_2$).

**Note**

It is very difficult to get the protractor arrow to line up exactly with the rays so your answer may be off a little.

**Exercise 3.4.3**

For the same angle you used in the previous two questions, move the protracter once again to the right edge of the material and measure the angle the ray leaves the material. How does this compare with the incident angle on the left?

## Exercise 3.4.4

Choose a different angle and use Snell's law to find the index of refraction outside the medium on the right. This time the incident angle will be inside the material at the right boundary, and $n_1$ will be the index inside the material (your answer to question two).

## Exercise 3.4.5

Drag the source inside the medium and try different angles. What do you notice?

When light goes from a material where the index is higher to a lower index there are angles for which the rays cannot leave the material. The angle at which a ray starts to reflect off the boundary instead of passing through is called the **angle of total internal reflection**. You can see this if you look at the surface of the water in a pool from under water; at a certian angle you see a reflection of the bottom of the pool instead of objects above the water. Total internal reflection is also why light remains in a fiber optic cable instead of being absorbed by the coating.

## Exercise 3.4.6

Find the angle for total internal reflection two ways. First experiment with the angle of incidence (source inside the medium) for a fixed index of refraction of $1.40$. At what incident angle does the ray reflect? You can also find the angle using $n_1 \sin \theta_1 = n_2 \sin \theta_2$ where $n_1$ is the index inside the medium and $\theta_2 = 90^\circ$. Do your two values match?