

## Chapter 07: Light

Physical Science, Tillery, 13<sup>th</sup> ed.

## Lab 10: Refraction

DUE: 02 July 2024

## Introduction

Light strikes a boundary: now what? We accept, almost without thought, that light passes through some materials so easily, the material cannot even be seen (like the air itself). We understand the transparency of air, water, and glass because we have endless experience with seeing through all three. And when we look through a window, what we see is what we expect. We don't generally notice any weird distortions or effects. But the path of a light ray is affected whenever it crosses from one medium (like air) to another (like glass or water).

Water and glass transmit light at a much slower speed than vacuum or air. It's the change in speed at the boundary that causes the path of the light ray to change, sometimes dramatically. Often this refraction is so small you never notice it.

No seals were harmed in the taking of this photograph, and it's not Photoshop. The extreme refraction you see here is the result of (on bottom) light bending at the water-glass boundary, and then again at the glass-air boundary. But the seal's head is seen only through the glass: air-glass bends the light, but then the glass-air transition bends it back. The different amounts of bending make the part below and the part above the water seem like two separate objects!

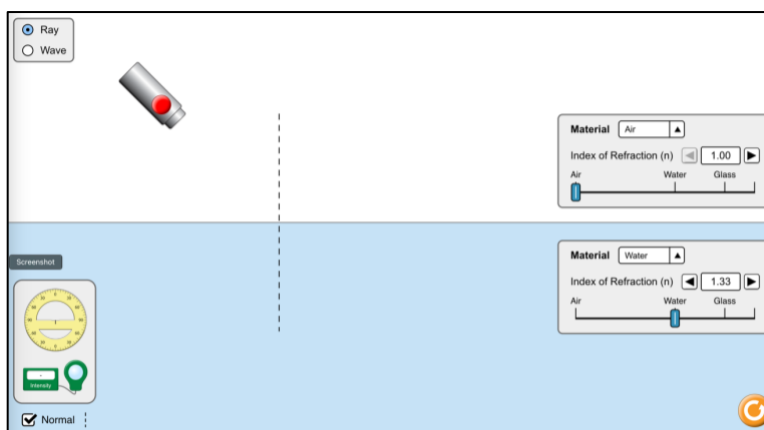


## Objectives

- Introduce the concept of refraction
- Define the index of refraction for a medium
- Demonstrate Snell's Law of refraction quantitatively
- Calculate the index of refraction for an unknown medium using Snell's Law
- Determine the conditions for total internal reflection

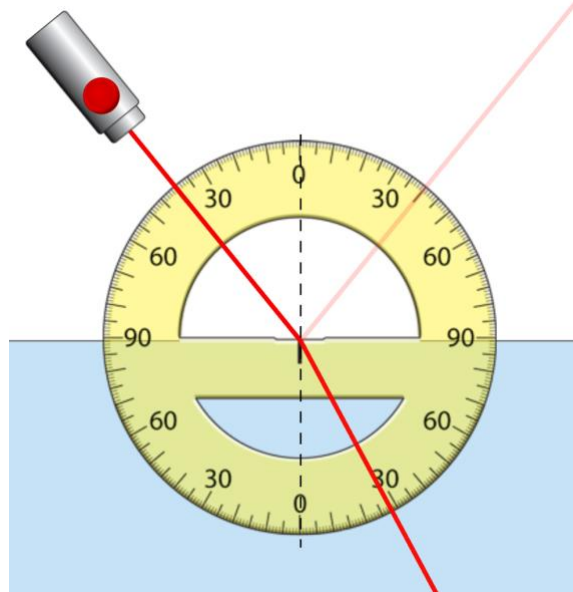
## Equipment

- Internet-capable device with the ability to run a browser
- Paper, pencil, calculator
- Scientific Calculator



## Procedure

1. Read this handout completely before you try to dive in. It will save you time and frustration later. If you are able to print it, you will not have to tab between windows—you can look at this and the refraction simulator at the same time.
2. Do you have paper and pencil handy? Don't forget your calculator.
3. In a browser window, navigate to the [PhET Bending Light Sim](#). Don't try to start doing the lab yet! Just verify that the interactive opens properly. Unfortunately, this particular sim does not have a downloadable App for your phone.
4. There are three simulations; click on the **Intro**. The figure above on the right shows what the interface looks like on the web page. You have two layers of different mediums and a laser pointer to create a narrow beam of light.
5. The dotted line is perpendicular to the interface, and you will drag and place the protractor right on the normal. Position the protractor carefully so that the horizontal line is exactly on the boundary between the media. Notice that the protractor measures angles with respect to the vertical. This is on purpose!
6. Tap the red button, and the laser shoots a beam. Notice that you see both the beam reflected off the surface, and the refracted beam that passes through. Check your protractor alignment by making sure that your angle of incidence is equal to the angle of refraction. See the figure above for what the correct alignment looks like! In this case, the angle of incidence is  $\theta_1 = 40^\circ$  and the angle of refraction is  $\theta_2 = 28^\circ$ .



## Questions

On the right, you can choose which medium you want to use, or select Custom to choose your own index of refraction. By default, the top medium is **AIR** and the bottom medium is **WATER**. Without recording any data, examine what happens to the beam of light when you change the position of the pointer. Try angles of incidence  $10^\circ$ ,  $20^\circ$ , and  $30^\circ$ .

- What happens when you increase the angle of incidence?
  - The larger the angle of incidence, the larger the angle of refraction.
  - As the angle of incidence gets larger, the angle of refraction gets smaller.
  - Nothing. The beam emerges at the same  $30^\circ$  angle, no matter what the angle of incidence.

Swap the two media, making the top medium **WATER** and the bottom medium **AIR**. Repeat your observations by testing out  $10^\circ$ ,  $20^\circ$ , and  $30^\circ$  angles of incidence.

- Now what happens when you increase the angle of incidence?
  - The larger the angle of incidence, the larger the angle of refraction.
  - As the angle of incidence gets larger, the angle of refraction gets smaller.
  - Nothing. The beam emerges at the same  $30^\circ$  angle, no matter what the angle of incidence.
- Did the same thing happen in each case?
  - Yes. It did not matter which medium was on top; the same incident angle always gave the same angle of refraction.
  - No. With air on top, all the angles got bigger. With water on top, all the angles got smaller.
  - Yes and no. In both cases, increasing the incident angle increased the refraction angle. But the refraction angles were not the same when the media were switched.

Make the top medium **AIR** again. The bottom medium should be either **WATER** ( $n = 1.33$ ) or **CUSTOM** (set the index to  $n = 1.60$ ).

- Using **AIR** as the top medium, compare **WATER** and **CUSTOM** as the bottom medium. Use an incident angle of  $\theta_1 = 50^\circ$ .
  - The angle of refraction was the same. With either water or custom, the angle was  $\theta_2 = 35^\circ$ .
  - The angle of refraction for water was much smaller than the refraction angle for custom.
  - The angle of refraction for custom was much smaller than the refraction angle for water.
- Which beam of light was bent more? By 'bent more' you are looking at the **difference** between where the beam started ( $\theta_1$ ) and where it emerged ( $\theta_2$ ), or bending =  $\theta_1 - \theta_2$ .
  - The medium (custom) with the higher index ( $n = 1.60$ ) bent the beam of light more.
  - The medium (water) with the lower index ( $n = 1.33$ ) bent the beam of light more.
  - The index did not make a difference. Both media bent the light by the same amount.

The index of refraction of a material is defined as  $n = \frac{c}{v}$  where  $c = 3 \times 10^8 \frac{\text{m}}{\text{s}}$  (the speed of light in a vacuum), and  $v$  is the speed of light through the medium. It's literally comparing the fastest speed possible ( $c$ , speed in vacuum) to the speed through the medium. Notice that because  $c$  is the fastest possible speed, the index will always be greater than 1 (the denominator must always be smaller than the numerator!).

- Use the index ( $n = 1.60$ ) to calculate the speed of light through the custom medium:  $v = \frac{c}{n}$ .
 

A) $v = 1.12 \times 10^8 \frac{\text{m}}{\text{s}}$	C) $v = 1.36 \times 10^8 \frac{\text{m}}{\text{s}}$	E) $v = 1.60 \times 10^8 \frac{\text{m}}{\text{s}}$
B) $v = 1.24 \times 10^8 \frac{\text{m}}{\text{s}}$	D) $v = 1.48 \times 10^8 \frac{\text{m}}{\text{s}}$	F) $v = 1.87 \times 10^8 \frac{\text{m}}{\text{s}}$
- True or false:** The higher the index of refraction, the slower light travels through the medium.

Complete the table below by adjusting only the angle of incidence ( $\theta_1$ ). Record the value of the angle of refraction ( $\theta_2$ ) for each incident angle. The top substance should be **AIR** ( $n_1 = 1.00$ ), and set the bottom substance to **CUSTOM** ( $n_2 = 1.47$ ).

QUESTION	ANGLE OF INCIDENCE $\theta_1$	ANGLE OF REFRACTION $\theta_2$	QUESTION	ANGLE OF INCIDENCE $\theta_1$	ANGLE OF REFRACTION $\theta_2$
	$10^\circ$	$7^\circ$	9	$30^\circ$	
8	$20^\circ$		10	$40^\circ$	

- What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 20^\circ$ ?
 

A) $\theta_2 = 7^\circ$	B) $\theta_2 = 13^\circ$	C) $\theta_2 = 19^\circ$	D) $\theta_2 = 25^\circ$
-------------------------	--------------------------	--------------------------	--------------------------
- What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 30^\circ$ ?
 

A) $\theta_2 = 7^\circ$	B) $\theta_2 = 13^\circ$	C) $\theta_2 = 19^\circ$	D) $\theta_2 = 25^\circ$
-------------------------	--------------------------	--------------------------	--------------------------
- What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 40^\circ$ ?
 

A) $\theta_2 = 7^\circ$	B) $\theta_2 = 13^\circ$	C) $\theta_2 = 19^\circ$	D) $\theta_2 = 25^\circ$
-------------------------	--------------------------	--------------------------	--------------------------

According to Snell's Law, the relationship between the incident and refracted beam can be expressed as:

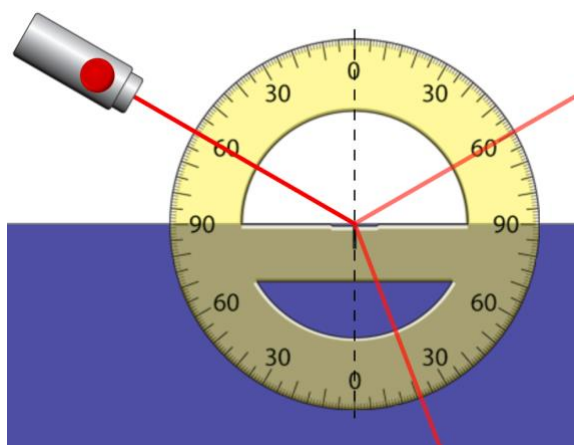
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where  $n_1$  is the index of refraction of the incident medium,  $\theta_1$  is the angle of incidence,  $n_2$  is the index of refraction of the refractive medium, and  $\theta_2$  is the angle of refraction. Re-write the equation to solve for  $n_2$ , and you get:

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

Snell used this method to begin measuring the indices of refraction for all kinds of different media. Notice that you have two unknown media that you can choose from. Let's find the index of refraction for one of these. Choose **AIR** ( $n_1 = 1.00$ ) for the top substance, and **MYSTERY A** ( $n_2 =$  unknown) for the bottom. As shown on the right, when you use an incident angle  $\theta_1 = 60^\circ$ , you should get an angle of refraction  $\theta_2 = 21^\circ$ .

Complete the table below with your observations of the refraction angles ( $\theta_2$ ), then calculate the index of refraction ( $n_2$ ) for each trial. Don't forget: make sure your calculator is in **DEGREE** mode and not radian mode!



QUESTION	ANGLE OF INCIDENCE $\theta_1$	ANGLE OF REFRACTION $\theta_2$	INDEX OF REFRACTION $n_2$	QUESTION	ANGLE OF INCIDENCE $\theta_1$	ANGLE OF REFRACTION $\theta_2$	INDEX OF REFRACTION $n_2$
11	10°			13	30°		
12	20°			14	40°		

11. What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 10^\circ$ ?  
 A)  $\theta_2 = 0^\circ$                       B)  $\theta_2 = 4^\circ$                       C)  $\theta_2 = 8^\circ$                       D)  $\theta_2 = 12^\circ$
12. What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 20^\circ$ ?  
 A)  $\theta_2 = 0^\circ$                       B)  $\theta_2 = 4^\circ$                       C)  $\theta_2 = 8^\circ$                       D)  $\theta_2 = 12^\circ$
13. What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 30^\circ$ ?  
 A)  $\theta_2 = 12^\circ$                       B)  $\theta_2 = 16^\circ$                       C)  $\theta_2 = 20^\circ$                       D)  $\theta_2 = 24^\circ$
14. What is the angle of refraction ( $\theta_2$ ) when  $\theta_1 = 40^\circ$ ?  
 A)  $\theta_2 = 12^\circ$                       B)  $\theta_2 = 16^\circ$                       C)  $\theta_2 = 20^\circ$                       D)  $\theta_2 = 24^\circ$
15. Calculate the **average value** for the index of refraction.  
 A)  $n_2 = 2.26$                       B)  $n_2 = 2.36$                       C)  $n_2 = 2.46$                       D)  $n_2 = 2.56$                       E)  $n_2 = 2.66$
16. Examine [this table of refractive indices](#) for a variety of materials. Identify your unknown material. This sample is most likely  
 A) Tantalum pentoxide.                      C) Diamond.                      E) Silicon carbide.  
 B) Strontium titanate.                      D) Titanium dioxide.                      F) Potassium niobate.

Surprise! You discover that the unknown sample was really composed of cubic zirconia (false diamond!). The true index for cubic zirconia is  $n_{CZ} = 2.15$ . (Which explains why CZ is not quite as sparkly as real diamond!) Compare your experimental average ( $n_2$  from Question 15) to this known value by calculating the % error:

$$\%error = \left[ \frac{n_{CZ} - n_2}{n_{CZ}} \right] \times 100$$

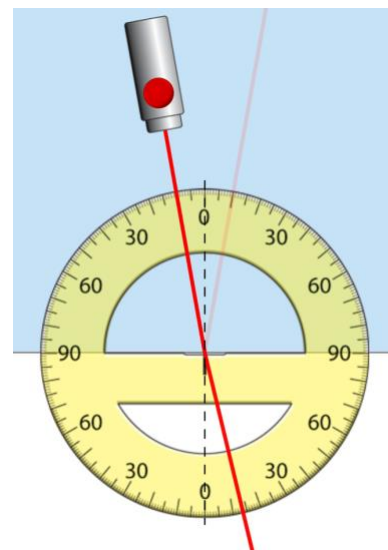
17. What is the **percent error** in your measured average value compared to the known value?  
 A)  $\%error = 0\%$                       C)  $\%error = 1.4\%$   
 B)  $\%error = 0.14\%$                       D)  $\%error = 14\%$

Total internal reflection happens when light strikes a boundary, and instead of passing through, it bounces back. Let's set up one more simulation to see how that happens. Notice above that **WATER** ( $n_1 = 1.33$ ) is the top medium, and **AIR** ( $n_2 = 1.00$ ) is the bottom. You should see that when  $\theta_1 = 10^\circ$ , the refraction angle  $\theta_2 = 14^\circ$ .

18. True or false: When  $\theta_1 = 35^\circ$ , the refraction angle  $\theta_2 = 50^\circ$ .
19. Examine what happens when you increase the angle of incidence (use  $10^\circ$  increments:  $20^\circ$ ,  $30^\circ$ ,  $40^\circ$ ,  $50^\circ$ ). What just happened?  
 A) Well, that was weird. The refracted ray suddenly disappeared!  
 B) Was something supposed to? The beam refracted just like in the previous examples!

The critical angle  $\theta_c$  is defined as the incident angle beyond which there is no refracted ray. The incident light strikes the boundary and completely reflects. It occurs when the refracted beam has an angle  $\theta_2 = 90^\circ$ . You can predict the critical angle using Snell's Law:

$$\begin{aligned} n_1 \sin \theta_c &= n_2 \sin \theta_2 = n_2 \sin(90^\circ) \\ n_1 \sin \theta_c &= n_2(1) \\ \sin \theta_c &= \frac{n_2}{n_1}, \quad \text{or} \quad \theta_c = \sin^{-1} \left( \frac{n_2}{n_1} \right) \end{aligned}$$



20. Predict the critical angle by calculating  $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$  for water. Water is the top (incident =  $n_1 = 1.33$ ) medium and air is the bottom (refractive =  $n_2 = 1.00$ ) medium.
- A)  $\theta_c = 38.8^\circ$                       C)  $\theta_c = 48.8^\circ$                       E)  $\theta_c = 58.8^\circ$   
B)  $\theta_c = 43.8^\circ$                       D)  $\theta_c = 53.8^\circ$                       F)  $\theta_c = 63.8^\circ$
21. Does this work both ways? Is there a critical angle for total internal reflection when air ( $n_1 = 1.00$ ) is the incident medium and water ( $n_2 = 1.33$ ) is the refractive medium?
- A) Yes. It does not matter which medium is on top or bottom; the critical angle is exactly the same.  
B) Yes and no. You will get total internal reflection, but with a different critical angle if you swap the media.  
C) No. You will only get total internal reflection when the incident medium has a higher index than the refractive medium.