Optics: Reflection and Refraction

Martin Liphardt

Edited by Diandra L. Leslie-Pelecky and Anne Starace

Abstract
This module teaches two important phenomena in optics, the reflection and refraction of light. The principles of lenses and prisms are explained. This module also contains an activity about total internal reflection and fiber optic communication.

Caution!
This activity uses a Laser.
Read the safety instructions before using this activity.
### Content Standards

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.2.1</td>
<td></td>
<td>4.2.1</td>
<td></td>
<td></td>
<td>8.2.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4.3.3</td>
</tr>
</tbody>
</table>

### History & Process Standards

<table>
<thead>
<tr>
<th></th>
<th>K</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Skills Used/Developed:**
# TABLE OF CONTENTS

I. OBJECTIVES...............................................................................................................................4

II. SAFETY ......................................................................................................................................4

III. LEVEL, TIME REQUIRED AND NUMBER OF PARTICIPANTS..............................................5

IV. LIST OF MATERIALS...............................................................................................................5

V. INTRODUCTION .....................................................................................................................5

VI. PROCEDURE..........................................................................................................................13

VII. FREQUENTLY ASKED QUESTIONS ................................................................................19

VIII. TROUBLE SHOUTING.........................................................................................................19

IX. REFERENCES ........................................................................................................................19

X. GLOSSARY OF TERMS ..........................................................................................................19

---

*Optics, Reflection and Refraction, V 3.0*

*Copyright the Board of Regents of the University of Nebraska 2002*
I. OBJECTIVES

Students will:
- measure the angle of incidence and angle of reflection of a reflected beam of light and realize that they are equal.
- observe the refraction of light traveling through different mediums.
- learn how the index of refraction is calculated.
- understand that energy is always conserved.
- learn that laser light is very intense and should never be shinned directly in eyes.

II. SAFETY

Glycerin is non-toxic but should not be ingested. If it comes into contact with eyes rinse thoroughly with water. Wash hands after coming into contact with glycerin.

Important! Please read!

Safety is an important issue in this demonstration because it involves the use of a laser. The laser(s) used in this demo are potentially harmful to the human eye even though their output power is probably less than 5 mW. They are potentially harmful because the output power is spread over a very small area compared to many other light sources. This causes the light intensity, the power per area, to be much higher. Here is an example:

<table>
<thead>
<tr>
<th>Light Power in Watt</th>
<th>Laser (5 x 10^{-3})</th>
<th>Light Bulb (50 W)</th>
<th>Flash light (1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area covered by light (m^2)</td>
<td>5 x 10^{-6}</td>
<td>50 (2 m from bulb)</td>
<td>0.01 (10 cm from the bulb)</td>
</tr>
<tr>
<td>Intensity (Watt/m^2)</td>
<td>1000</td>
<td>0.1</td>
<td>100</td>
</tr>
</tbody>
</table>

As you can see, the intensity of the light from the laser is much higher than that of the light bulb at a distance of 2 meters. The light from a flashlight at short range is also relatively high and is intense enough to cause us to see stars for a while when directed into the eye. The laser light is more intense and can cause more permanent damage to the eye. This demo involves focusing the laser light with a lens, which further increases the light intensity. So be careful!

If you bring along another laser make sure you know its output power rating and its laser class rating. If you do not understand this, do not bring another laser.
Alcohol: If you are doing the refraction-mixing demo, you will be using methyl and benzyl alcohol. Avoid skin and eye contact. Do not let the audience members use, smell or touch the alcohols. Make sure that you dispose of the used alcohol by bringing it back to the university with you. DO NOT dump the used alcohol down the sink!!!

III. LEVEL, TIME REQUIRED AND NUMBER OF PARTICIPANTS

**LEVEL:**
The students should be at least in 5th grade. There is no recommended upper limit, although older high school students may not be as interested if they have already seen similar demonstrations.

**TIME REQUIRED**
20-40 minutes

**NUMBER OF PARTICIPANTS**
No more than 25 students. The fewer students the closer they can come to the optics set-up to see better.

IV. LIST OF MATERIALS

| Water tank w/ scattering agent (Edmund Scientific) | 2 lenses |
| prisms w/ stand | semi-conductor laser w/ 4 AA batteries |
| 2 mirrors | optical fiber |
| screen (that fits in tank) | total internal reflection device |
| mirror on block | Cork board |
| pushpins | |

V. INTRODUCTION

Optics plays an important part in our society. Everybody relies on simple optics principles every day. The focusing action of the eye, based on the refraction of light, enables us to see. Mirrors, which reflect light, are also used daily.

A. REFLECTION

When light is incident upon the surface of a material (any material) some of the light will enter the material and some of the light will be reflected – that is "bounce" off of the surface much like a pool ball bounces off of the sides of a pool table. Just as is the case with a pool ball hitting the
side of a pool table, the angle of incidence of light equals angle of reflection. Sunlight reflected by a water surface or light reflected by a mirror are good examples of reflection. Although the details of the reflection process are quite complicated, we can learn a lot by making some simple observations. You can observe reflection using a mirror and some pushpins and by using the laser and water tank. (See activity B.1)

![Angle of incidence equals Angle of reflection diagram]

B. REFRACTION

The refraction of light is based on the interaction of light with matter. Unlike absorption, which causes a decrease of the light intensity as light travels through the medium (e.g. a pair of sunglasses), refraction leaves the intensity of the light unchanged but affects the speed at which light travels. In a vacuum, light travels at $3 \times 10^8$ meters/second. We call this quantity $c$. In a medium, light does not travel at $c$. Some of the photons, “pieces” of light, run into molecules and are re-emitted, and others go in the space between molecules. The photons that are re-emitted are going at a different speed than the photons that are traveling between the molecules. When we combine the speeds of the individual photons, we get a value for the overall speed of light through a certain medium. The overall speed of light changes when light goes through different mediums. The index of refraction, $n$, for a medium is the ratio between the speed of light in a vacuum, $c$, and the speed of light in that medium.

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the particular medium}}$$

When light goes from a material with one index of refraction to a material with a different index of refraction, it bends. The greater the difference of the indexes of refraction between the materials, the more the light bends. As far as we know, nothing can go faster than light in a vacuum, so the index of refraction is always a number greater than one. The indices of refraction of some common materials are shown in the table below. (Note: the speed of light in air is so close to that of vacuum that we usually treat them as being the same.)
This difference in speed of light in different substances or media (e.g. air, water, glass...) causes the light to change direction or "bend" when it travels from one medium to another. This is known as \textit{refraction}, and is illustrated in the following figure:

The light wave that travels from medium 1 to medium 2 changes direction at the interface because the speed of light in medium 1, $v_1$, is different (in this case faster) than the speed of light in medium 2, $v_2$. A Dutch mathematician named Willebrord Snell figured out that the angle the incident light makes with the normal (perpendicular line) ($\theta_1$) is related to the angle the refracted light names with the normal ($\theta_2$) according to:

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

This is known as Snell’s law.

$\theta_2$ is always a positive angle and is always measured from the normal. Although the actual numbers aren’t important for this demonstration, the equation does tell us that:

\begin{table}[h]
\centering
\begin{tabular}{|l|c|}
\hline
\textbf{Material} & \textbf{n} \\
\hline
Hydrogen (1 atm, 0° C) & 1.0001 \\
Air (1 atm, 0° C) & 1.0003 \\
\text{CO}_2 \text{ (1 atm, 0° C)} & 1.0005 \\
Water (20°C) & 1.333 \\
Methyl Alcohol & 1.33 \\
Ethyl Alcohol & 1.362 \\
Ice (0°C) & 1.31 \\
Opal & 1.44-1.46 \\
Glycerine & 1.473 \\
Acrylic & 1.49 \\
Amber & 1.54 \\
Benzyl Alcohol & 1.54 \\
Polystyrene & 1.59 \\
Glass & 1.5-1.75 \\
Garnet & 1.73-1.89 \\
Cubic Zirconia & 2.15 \\
Diamond & 2.417 \\
\hline
\end{tabular}
\end{table}
- When light goes from a material with a smaller index of refraction to one with a larger index of refraction, the rays are bent **toward** the normal.
- When light goes from a material with a larger index of refraction to one with a smaller index of refraction, the rays are bent **away** from the normal.

We often represent the path that light takes as a ray so that we can see where the light is going.

The diagram below shows a number of rays refracting as they cross a surface.

![Diagram of light ray refraction](image)

In the figure above, the lowest of the three rays is just entering medium 2. At that point, the light slows down (if we assume that the speed of light in medium 2 is slower than that of medium 1).

The light in the upper portion of the wave has not yet entered medium 2 and therefore continues to travel at the higher speed. At a certain time later the upper portion will have just reached the interface. The distance \( a \) traveled by the upper portion of the wave is greater than the distance \( b \) traveled by the lower portion of the wave because of the difference in speed. As a result, all of the rays now travel in different directions. The following simple mechanical analogy might be useful in explaining this:

**Mechanical Analogy:**

A car travels in a straight line on a concrete road. The concrete road ends and becomes a sandy beach. We take a few measurements and determine that the car travels at a slower speed in sand compared to the concrete surface. Now, if the car were to travel from the concrete road to the beach in a fashion that the front right wheel first enters the sand (i.e. the car does not enter the sand head on but at an angle), you expect that this wheel will slow down. Because this wheel is connected to the rest of the car we can imagine that the slowing down of that wheel will cause the whole car to slightly change direction. After all 4 wheels are on the sand the car will once again travel in a straight line except that a slight change in direction took place at the concrete/sand interface. This is very similar to the refraction of a light wave at say an air/glass
interface. Refraction can only take place when the wave is incident other than normal (head on). A car that enters the beach head-on will simply slow down without changing directions.

**C. TOTAL INTERNAL REFLECTION**

Total internal reflection can occur when light travels from a medium in which light moves at a lower speed to a medium in which light moves with a higher speed. This corresponds to moving from a medium with a larger value of \( n \) to a medium with a smaller value of \( n \). The medium with the lower speed of light is said to have a greater *optical density*. If you consider how fast an object (e.g. a bullet) would move in liquids of different density (e.g. water and rubber cement), this terminology makes sense. As mentioned above, the refracted wave makes a greater angle with the normal than the incident wave, as shown in the figure.

If you were to increase the angle of incidence (i.e. make the light wave come in at an ever shallower angle) there will be some angle at which Snell’s Law would require the refracted wave to travel parallel to the surface after refraction. Such a wave cannot exist, so the incident wave does not penetrate the second medium. This is true for light that is incident at an angle that is equal to or greater than this critical angle. Because none of the light can be lost (conservation of energy) we conclude that all of the light must be reflected; hence the term total reflection. The word "internal" is added to signify that from the viewpoint of medium 1 the light stays inside. The figure shows what happens as the angle of incidence gets larger and larger. The angle of the incident ray at which the light would be reflected parallel to the interface between the two media is called the *critical angle*. For angles greater than the critical angle, we say that all of the light is totally internally reflected. Total internal reflection has very useful applications. If I were to surround a medium of higher optical density with a medium of lower optical density, light would
stay inside medium 1 as long as the angles of incidence are greater than the angle of total internal reflection. Such a device in the form of a long cable is known as an optical fiber. It looks and works like this:

The light that goes into the fiber totally reflects at the interface between the core of the fiber (with index of refraction $n_1$) and the surrounding medium (with index of refraction $n_2$). The path of the light thus follows the shape of the fiber instead of traveling in a straight line. With such a device, light can move from one place to another without the need for a direct line of sight between the two places. This allows light to be directed around obstacles.

Communication using fiber optics is very efficient because very little light is lost in the process of total internal reflection. The best mirrors reflect about 90% of the light, which means that 10% of the light is lost. If you start with a weak signal, every time the light is reflected from a conventional mirror, you will lose some of your signal. If the light reflects many times, you will lose all of the signal. In total internal reflection, much less light is lost, so the signal can be transmitted much greater distances without loss of quality.

Fiber optic communication was developed by Normal French at AT&T in 1934. The communications industry has taken advantage of total internal reflection by building

---

1 Contemporary College Physics 2nd Ed, Edward R. Jones and Richard L. Childers, Addison-Wesley
communication devices that are not based on electromagnetic signals traveling along lossy (causing attenuation or dissipation of electrical energy) electrical wires but based on fiber optics. You may have heard about the Morse code. It's a code where each letter of the alphabet is represented by a series of two signals of different length (short and long). All we need for this type of communication to work is an on/off switch on our light source and an optical fiber. The light from the light source is injected into the fiber and travels to the observer who looks into the fiber to see the light go on and off.

A fiber optic cable consists of a bundle of these glass fibers, each of which is capable of transmitting messages at close to the speed of light. Fiber optics has several advantages over traditional metal communications lines, including the ability to carry more data, being more resistant of interference, and being thinner and lighter than metal wires. Their primary disadvantage is that they are expensive to install, are more fragile than metal wire and are difficult to split. Fiber optics is a particularly popular technology for local-area networks and telephone lines.
**Total Internal Reflection is forever.** Another interesting application of total internal reflection is in cutting diamonds and other gemstones. The minimum angle of incidence for total internal reflection is the smallest for diamond because the index of refraction is so large compared to that of air. Diamonds are cut to take advantage of this, so that when light is totally internally reflected, it is incident upon another facet of the diamond at an angle greater than \( \theta_c \) (24.4°). This means that light entering the diamond undergoes many, many reflections before it exits the diamond (and the shape is such that the light is much more likely to exit at the top of the diamond that out the sides). This is what gives a diamond its sparkle. Imperfections or flaws in diamonds are due to defects in the crystal structure. These defects can scatter light, ruining the arrangement set up to ensure total internal reflection. This is why poorer quality diamonds don’t sparkle as much.

**Left:** a diamond cut in the correct proportions. Notice how the light that comes in totally internally reflects, then comes out again

**Middle:** Too deeply cut. The light doesn’t internally reflect when it hits the right side of the diamond and it passes into the air

**Right:** Too shallow. The light doesn’t even internally reflect on the first reflection.
VI. PROCEDURE

A. SETUP

Preparation of water tank: Fill tank 3/4 to 4/5 full with cold water. Use the lid of the bottle that contains the scattering agent (milky looking liquid) to add a small amount (1/4 of a lid is sufficient) of the scattering agent to the water in the tank and mix until dissolved. Do not add too much of the scattering agent! Use the laser to determine if more or less scattering agent is needed. In a darkened room the best mixture is obtained when the laser beam is visible over a distance of about 10 inches in the water/scattering agent mixture. If it is visible for less (more) than 10 inches add water (scattering agent).

Preparation of diode laser: Before you leave check that the laser is operational. It is powered by 4 AA batteries and has a rocker switch mounted on the battery housing for on/off operation. I recommend turning the laser off during the demo when not in use (to prolong its life but also for safety reasons).

Note:
The light from the diode laser is linearly polarized; the light waves are in the same plane. The visibility of the laser beam in the water tank depends strongly on the orientation of the plane of polarization with respect to the observer. Rotate the diode laser on its own axis and observe the brightness of the beam inside the water tank. Find the position that gives the brightest beam and clamp the laser in this position using the holder. When making these observations please make sure that you look at the laser beam in the tank from the same viewpoint as the audience does. The exact angle is not that critical, but if you look into the tank from the top and the audience from the front you will actually minimize the visibility of the laser beam for the audience. (The explanation of the polarization dependence is not part of this module, but if you are interested you might want to look up an Optics or Physics text book on polarization scattering and dipole radiation.)

B. EXECUTION

REFLECTION

For a small group:
a. Place a mirror upright on a piece of paper on top of the corkboard.
b. Hold the laser (or a laser pointer) using a clamp at some angle so that it strikes the mirror.
c. Have the audience members draw a line on the paper that represents the incoming wave. Label the wave “incoming light”

d. The light will reflect off the mirror and the student should be able to see the path of reflection. Have them draw this ray. Label this ray “reflected light”.

e. Have them draw a line that is perpendicular to the face of the mirror and label this line “normal” (perpendicular).

f. Label the angle between the incident ray and the normal “θi” and the angle between the reflected ray and the normal “θr”

g. Draw a line at the face of the mirror.

h. Turn off the laser

i. Your sheet of paper should look like the following diagram:

j. Measure the angles θi and θr. They should be about equal, which shows that

\[ θ_i = θ_r \]

For large or small groups.
Using the water tank set-up, set a mirror flat on the bottom of the tank with the mirrored surface pointing upward. Change the angle of incidence by moving the laser up and down. The students should see the angle of the reflected light changing.

At this point I’d like to remind you that the light of the laser you are handling is potentially dangerous to the human eye. Please be sure you know where the laser beam and all the "stray" beams are going.
**Refraction:**

-Shine the laser beam onto a prism placed on a pedestal:

Vary the angle of incidence and point out the change in direction of the laser beam after it passed through the prism. Explain this in terms of refraction using the explanation (mechanical analogy) in the introductory section.

Shine the laser beam into the tank of water at an angle. With the lights out, you should see the refracted beam in the water. Point out the air-water interface and remind audience that water has a larger index of refraction than air, so the light is refracted toward the normal.
**Refraction Matching.** (thanks to Stephen Ducharme for this demo).

**Note:** You have to get benzyl and methyl alcohol from the safety cabinet in 362 Behlen. Check well before going to make sure that there is some there!

a. Place 4.25 parts benzyl alcohol in beaker.
b. Place a few glass marbles in the beaker and roll the solution around.
c. Slowly add up to one part methyl alcohol, watching carefully to see when the marble ‘disappears’
d. Professor Ducharme recommends exclaiming at this point, “I’ve lost my marbles”

Explanation. Silica (non-leaded) glass has an index of refraction around 1.5. The index of refraction of benzyl alcohol is 1.54 and of methyl alcohol is 1.33. Mixing the two liquids together will give you a liquid with an index of refraction very close to the index of refraction of the marble and you won’t be able to see the marble anymore. What you want is for \( n_{\text{mix}} = n_{\text{glass}} \)

\[
\frac{c_{\text{Benzyl Alcohol}}}{c_{\text{Methyl Alcohol}}} = \frac{n_{\text{glass}} - n_{\text{Methyl Alcohol}}}{n_{\text{Benzyl Alcohol}} - n_{\text{glass}}}
\]

This where the 4.25:1 ratio comes from.

Clean up: Place the mixture of used alcohols in the storage bottle. When you return, transfer the mix to the waste alcohol bottle in BeL 362.

**Variation:**

**List of Materials**
600 ml Pyrex beaker
250 ml Pyrex beaker
bottle of glycerin

**Execution**
Put 250 ml beaker into 600 ml beaker containing glycerin. The 100 ml beaker becomes invisible.

**Cleanup**
Remove the small beaker from the glycerin and put it on a paper towel. Pour the excess glycerin back into the bottle marked "glycerin". Wash both beakers with soap and water.
**Total internal reflection:**

Place a screen inside the tank and shine the laser beam into the tank at a steep upward angle so that it reflects at the water/air interface. You might need to place the tank near the edge of a table so that you can hold the laser below the surface level of the table.

If the angle is steep enough, you should see two spots on the screen. The lower one is from the beam that is reflected at the water/air interface, the top one is from the beam that is refracted at the interface. If you make the angle shallower and shallower you should observe that the top spot is moving closer towards the water surface as you do so until it disappears at some point when the angle becomes too shallow. This is the critical angle for total internal reflection. Now all the light is reflected at the water/air interface (only one spot visible on the screen). Note that the bottom spot is brighter when total internal reflection takes place compared to when some of the light is refracted at the surface to produce the top spot (energy conservation!).

**Fiber Optics** Use the short length of optical fiber and try to inject the laser light into it. This is a bit tricky, and you might want to use the "third hand" to hold the laser or the fiber or both.
When successful you will notice that the whole fiber glows red and the other end of the fiber is bright red. The light that comes out of the other end is probably not bright enough to shine onto a screen for the audience to see. Instead the audience needs to really look at the other end and see the light come out.

**Total Internal Reflection Spiral.** The total internal reflection spiral is a large plexiglass rod that is shaped in a spiral. If you shine laser light in one end, you can see if travel around the spiral. Near where the light is injected, you can see the total internal reflection (usually requires the lights to be out). The light will come out the other end. This is not as efficient as the fiber optic, but is much larger.

**C. CLEANUP** Empty the tank and dry all optical elements. The scattering agent leaves a film on the inside walls of the tank, so make sure to wipe the inside of the tank thoroughly after it is empty.

If you did the refraction mixing demonstration, place the mixture of used alcohols in the storage bottle and bring it back with you. When you return, transfer the mix to the waste alcohol bottle in Behlen 362.
VII. FREQUENTLY ASKED QUESTIONS

VIII. TROUBLE SHOOTING
Laser does not work:
• Make sure the batteries are charged
• Check all electrical connections. If batteries and wiring are o.k. laser needs to be examined by authorized personnel.

IX. REFERENCES
For some interesting web sites:
http://www.ee.vt.edu/ee/research/fiber.html is the Virginia Tech Department of Electrical Engineering, one of the largest research centers on fiber optics.

X. GLOSSARY OF TERMS