Light and Color –
Reflection and Refraction:
Laboratory for Secondary Level Students
Student Manual

WOMEN SUPPORTING
WOMEN IN THE SCIENCES

Meet a Scientist

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About me:

I have a B.S. in Mechanical Engineering from the University of Dar es Salaam, and a Master's and PhD in Textile Technology from the University of Manchester and the University of Leeds in the UK. My passion for science grew in secondary school when I was able to conduct laboratory experiments. The practical application of science really fascinated me and made me realize that science is part of our everyday life. From that time, I have never looked back. I am a wife and a mother to two beautiful daughters.

When I was young …

My dad, a Civil Engineer, and my mom, an Economist, encouraged me to pursue math and science. I remember my dad pushed me to get all my math questions correct. As a young girl, I initially wanted to be a pilot, but having no female role models at that time and with the absence of a pilot training institute in Tanzania, my dad advised me to go for Engineering.

My advice for students interested in science:

Always go for your passion.

Mission Statement

This laboratory describes how light behaves when it encounters matter, specifically how light bounces off matter (reflection) and how light bends after passing through matter (refraction). The intended audience is secondary level students (ages ~12-18).

Contents

1. Introduction to WS2 Laboratories

1.1. Information about WS2

Women Supporting Women in the Sciences (WS2), an international organization unifying and supporting graduate and professional-level women and allies in science, technology, engineering, and mathematics (STEM), was awarded an American Physical Society (APS) Innovation Fund in 2020 to form international teams to design and distribute low-cost physics and materials science lab kits to 5000 primary and secondary school students, predominantly in eastern Africa. The lab kits are intended to utilize local resources and include topics that are especially relevant to young girls in order to spur their interest in STEM subjects. The international teams, which designed the content found in these laboratory manuals, worked with WS2 Partners in eastern Africa in order to successfully deliver and teach the science lab kits to their local communities through 2022. WS2 gratefully acknowledges the hard work of the teams in the creation of this lab kit content. For more information about WS2, please visit our website at ws2global.org.

WS2 is sponsored by the APS Innovation Fund, Northwestern University Materials Research Science and Engineering Center, and Northwestern University Multicultural Student Affairs. WS2 Partners receiving lab kits are representatives from Makerere University (Uganda), Masinde Muliro University of Science and Technology (Kenya), Mbeya University of Science and Technology (Tanzania), Mkwawa University College of Education (Tanzania), Nelson Mandela African Institution for Science and Technology (Tanzania), University of Dar es Salaam (Tanzania), University of Dodoma (Tanzania), and University of Rwanda (Rwanda). The APS, Materials World Modules, SciBridge, and Projekt Inspire have provided valuable input on WS2 lab kit design. WS2 especially thanks WS2 Partner representatives (John Bakayana, Pendo Bigambo, Daudi Mazengo, Lawrence Robert Msalilwa, Celine Omondi, Marcellin Rutegwa), Tom Coon and students of Haile-Manas Academy (Debre Birhan, Ethiopia), and Carla Johnston and students of Frank Bergman Elementary School (Manhattan, KS, USA) for piloting the lab kits with small focus groups in late 2021. WS2 also tremendously thanks the virtual lab kit design team that created the content for this lab manual.

1.2. Key Vocabulary

- Light: a form of electromagnetic radiation that makes objects visible
- Reflection: the bouncing back of a light ray off a surface without being absorbed
- Refraction: the bending of light as it changes speed and moves from one medium through another medium
- Wavelength: distance between two identical points on the wave; each color has a distinct wavelength
- Prism: a transparent object with two planar surfaces made at an angle (i.e., refracting surfaces) that separate white light into a spectrum of colors
- Laser: an intense monochromatic light source that contains only one color or wavelength of light

1.3. Key Questions

- What is the difference between reflection and refraction of light?

- What is the law of reflection?

- What does Snell's law describe?

1.4. Purpose

In this laboratory, students will learn the basics of reflection and refraction. These concepts are relevant to optics, understanding color from visible light, and many everyday life phenomena including lenses, mirrors, and pools of water.

2. Background on Main Topics

2.1. Light and Color

Light is a form of electromagnetic radiation that makes objects visible. Light rays travel in a straight line unless they are acted upon by a medium. For instance, light can travel through one medium, like air, and reflect/bounce off another medium, or it can travel through one medium and refract/bend as it travels through another medium. If the light rays bounce off the second medium, it is called reflection but if they travel through the second medium, it is called refraction.

Light bouncing back (i.e., reflecting) off an object and into our eyes enables us to see a particular object. One cannot see an object in the dark, because in the dark there is no light which can be bounced back to our eyes. On the other hand, bending of light rays (i.e., refracting) causes the objects to appear bent, or closer or larger than they really are.

White light or sunlight is composed of many colors which can be seen when light interacts with an object. However, there are many types of "light" (e.g., radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays and gamma rays), each with different wavelengths. Wavelength is the distance between two identical points on the wave. Human eyes can only detect a small number of wavelengths (e.g., visible light), and these are experienced by humans as seeing colors. These colors (in order of decreasing wavelength) are Red, Orange, Yellow, Green, Blue, Indigo and Violet, easily remembered by their first letters ROYGBIV. When combined, the different wavelengths of colors of light are undetectable; however, by using a triangular prism, one can see all the colors present in white light separately, as will be discussed in the next section.

2.2. Reflection and Refraction

When light rays fall on an object, they are reflected (bounced back) and enter our eyes. This produces the sensation of vision. Reflection of light occurs when light bounces off an object. If the surface of the object is smooth and shiny such as glass, water or polished metal, the light will reflect at the same angle as it hit the surface. This is the law of reflection of light which states that "the angle of the reflected ray is equal to the angle of the incident ray". The diagram below (Figure 1) illustrates the law of reflection, where the incident ray is the ray of light which falls on the object while the reflection ray is the ray of light that bounces back.

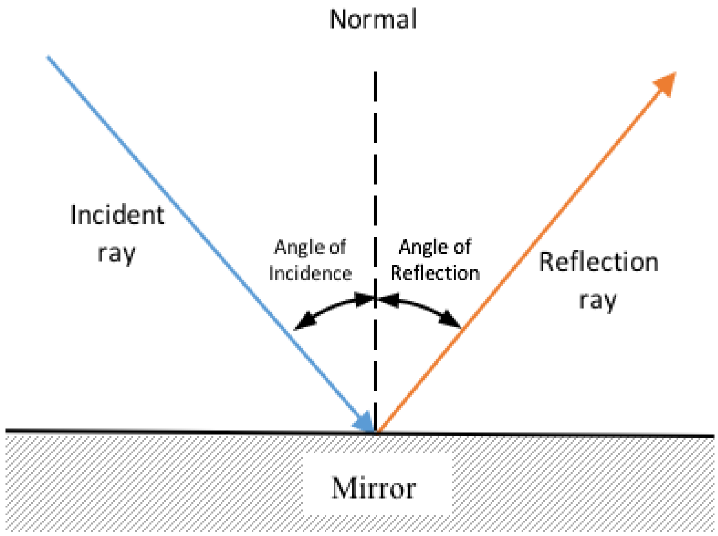


Figure 1. Reflection of light and illustration of law of reflection that shows the angle of the reflected light ray is equal to the angle of the incident light ray.

Light waves travel very quickly. However, when light hits objects, some of the objects may allow it to move at a constant speed while others may slow it down. When the light velocity changes, the light bends, a phenomenon known as refraction. This causes the objects to appear bent and perhaps closer or larger than they really are!

The degree to which light bends depends on how much it is slowed down, which means different objects or surfaces have different factors by which the speed of light is reduced compared to light in a vacuum. This factor is known as a refractive index. The refractive index is calculated using the equation $n = c/v$, with n being the refractive index, c the velocity of light in vacuum/air and v the velocity of light in a medium. The relationship describing the refractive indices of two materials and incident angles of light hitting the interface between these two materials (see Figure 2) is called Snell's Law: $n_1 * \sin \Theta_1 = n_2 * \sin \Theta_2$. In this equation, n_1 and n_2 are the refractive indices of the two materials, and Θ_1 and Θ_2 are the incident angles of light as measured from the normal (i.e., perpendicular – intersecting at 90 degrees –to the interface between the two materials).

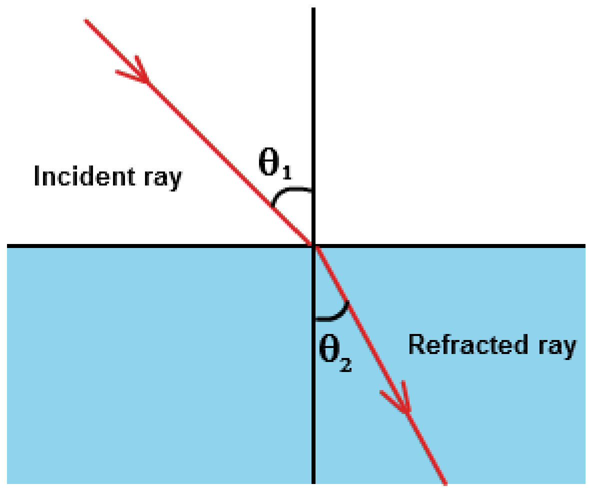


Figure 2. Illustration of Snell's Law that describes the relationship between two materials and their indices of refraction and incident angles of light that crosses their interface.

The use of a prism to split light into its individual colors is a good example of refraction (see Figure 3). A prism is a transparent object with two planar surfaces made at an angle (i.e., refracting surfaces) that separate white light into a spectrum of colors. Light travels slower through glass than air or vacuum and the light is bent or refracted twice as it enters and exits the prism. Each color of light has a different wavelength and travels at a different speed in the glass medium, and as such, the angle of refraction is different for each color. The second dispersion of light creates the colorful spectrum of colors from white light or sunlight. While white light contains all the colors of the rainbow, a laser is a monochromatic light source that contains only one color or wavelength of light. Lasers generate intense beams of light, so proper safety precautions must be taken to never look directly at a laser light source.

There are many real-life instances in which light refraction is important, including:

- Pool of water appearing less deep than it is:
    - Light travels from the bottom of the pool, through the water, then through the air into our eye. It travels in such a way that the pool often appears to be shallower than it really is, which can be hazardous for anyone jumping into pools with unknown depths.
- Rainbow formation in the sky:
    - When the air is full of water (e.g., after rainfall), the water droplets act like prisms creating a display of the colors of light.
- Microscope or telescope lenses:
    - These objects use refraction of light to make things appear closer than they really are. The lenses are curved in a way that magnifies small objects or those far away so that they are easily seen by human eyes.
- Eyeglasses/contacts:
    - These devices are made with special materials that bend and refract light in ways that improve vision. For example, bifocals use convex lenses to bend light hence making objects look bigger.

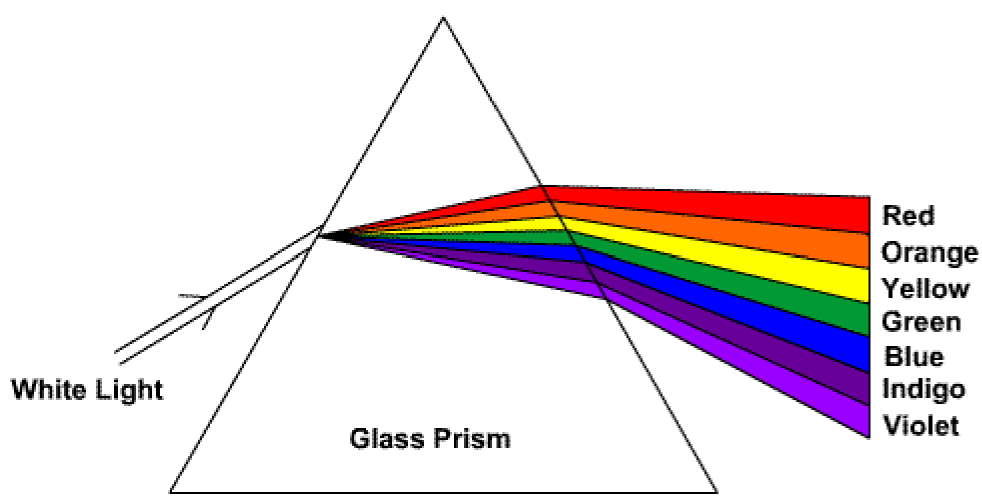


Figure 3. Refraction of white light through a prism leads to the creation of the colors of the rainbow.

2.3. Protractor Guide

If you have not used a protractor in some time, this section is intended as a quick guide to remind you how to measure an angle and draw a specific angle. Both skills will be necessary in the following experiments. Figure 4 shows an example of an angle being investigated with a protractor.

Measuring an angle:

1. Approximate the measure of your angle – acute (narrow angles less than 90 degrees), obtuse (wide angles more than 90 degrees), right (90 degrees). This helps as a check for you later. Additionally, if your protractor has two scales on the inside and outside of the protractor, you now know which to use.
2. Place the origin of the protractor (typically a small hole) over the center point, or vertex, of the angle you want to measure.
3. Align the protractor with the baseline of the angle. This means the baseline of the angle you want to measure should pass through zero on your protractor.
4. Follow the other leg of the angle to the measurement ticks on the protractor. If needed, you can extend this leg out farther by using a straight ruler or the bottom of the protractor. The number that this leg passes through is the angle's measurement in degrees. Check if this angle matches with your approximate guess from step 1 to ensure you are using the proper scale on your protractor. If your protractor does not have two scales and you have measured an obtuse angle when you know the angle is acute (or vice versa), you also have the option of subtracting the angle you measured from 180 degrees (the angle of a straight line) to get to the correct angle.

Drawing an angle:

1. Draw a straight line using the flat edge of your protractor. This line is the first leg of your angle.
2. Place the origin of the protractor (typically a small hole) at the end of the line you drew. This is your angle's vertex.
3. Using the protractor's measurement ticks, make a mark at the angle you wish to draw. Choose your protractor scale carefully. Recall for an acute angle, the scale will give you an angle less than 90 degrees, while for an obtuse angle, the scale will give you an angle greater than 90 degrees.
4. Draw the second leg of the angle by lining the bottom of the protractor up with the vertex and the mark you made in step 3.

5. Verify the angle you drew using the previous steps under "Measuring an angle".

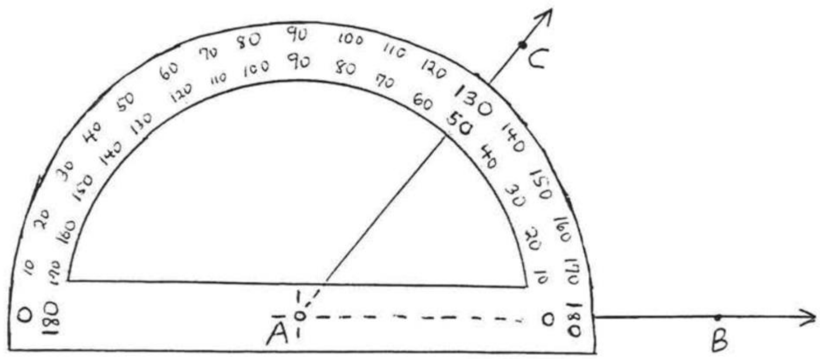


Figure 4. Protractor measuring acute angle. Point A represents the vertex of the angle. The line from A to B is the horizontal baseline of the angle passing through 0 degrees. The line from A to C intersects with the measurement of the angle in degrees (in this case about 50 degrees).

2.4. Sources

https://scienceworld.wolfram.com/physics/SnellsLaw.html

https://www.britannica.com/science/light/Reflection-and-refraction

https://www.sciencebuddies.org/science-fair-projects/project-ideas/Phys_p009/physics/using-a-laser-to-measure-the-speed-of-light-in-gelatin

https://www.wikihow.com/Use-a-Protractor

2.5. Supplies List

- Clear drinking glasses/glass jars
- Square glass/plastic container
- Cardboard
- Laser pointer (Class 2 or lower)
- Light source (e.g., sunlight, lamp)
- Paper (lined or unlined)
- Pencils
- Plane mirror with stand (could be heavy book or board)
- Protractor

- Water
- Sugar (alternative: canola or other oil)
- Scissors
- Prism (optional)

2.6. Safety Information

Before the students begin the laboratory, please take into consideration the following safety concerns:

- Students should never look directly at the Sun. This can permanently damage their eyes. If you are using the Sun as a light source, have the students look at a sunny spot on the ground or at the horizon away from the direction of the Sun.
- Students should never look directly at a laser point, as this can also permanently damage their eyes due to the laser intensity and emission as a tight beam.

3. Experiments

3.1. Part I. Light and Reflection

3.1.1. *Summary*

This experiment will guide students to prove the law of reflection of light.

3.1.2. *Pre-Experiment Questions*

1. What is light?

a. Extension: What are some facts about light or sunlight?

2. What is the law of reflection of light?

a. Extension: Draw the law of reflection in action assuming a light ray is incident on a mirror. Label the incoming and outgoing ray and angles.

3. What are examples of reflection from your life?

3.1.3. Materials

- Laser pointer or other light source (e.g., torch, cell phone light)
- Plane mirror with stand/book
- Protractor
- Paper
- Pen/pencil

3.1.4. Procedure (2-4 students per group)

1. Draw a straight horizontal line on the paper using the protractor. Label this line "1".
2. Draw a perpendicular line (recall perpendicular means "normal" or intersecting at 90 degrees) at the middle of the horizontal line you drew using the protractor (see Figure 5). Label this line "2".
3. Measure a 15-degree angle using line "2" as your zero-degree baseline and vertex at the point where lines "1" and "2" intersect. Label this line "3", which represents your incident ray line (see Figure 6). This angle represents your angle of incidence (θ_i).
4. Stand the plane mirror upright on its longest side on line "1". If you have a stand, use this to hold up the plane mirror; otherwise, you can use a book or another sturdy object to hold up the mirror. Try to keep the mirror as upright as possible and be sure the mirror side (not glass side) is pressed up as close as possible to line "1".
5. Direct the laser pointer along line "3" and toward the vertex of "1" and "2". To keep the laser pointer steady, try laying it on the surface on which the plane mirror is standing. Note: If you do not have a laser pointer, you may need to collimate your cell phone or torch light with a piece of cardboard and a small hole (i.e., place the cardboard with small hole between the light source and the mirror to create a beam of light).
6. Mark the reflected path of light using dots and your pen/pencil. To make this easier, look at where the laser light hits your pen/pencil.
7. Connect the dots into a straight line that passes through the vertex of this new line and line "2". Label this line "4". This is your reflected ray.
8. Record the angle of reflection (θ_r) in your table in Results.

9. Repeat steps 3-8 with other angles of incidence (30-degrees, 45-degrees, and any other angles you want to try).

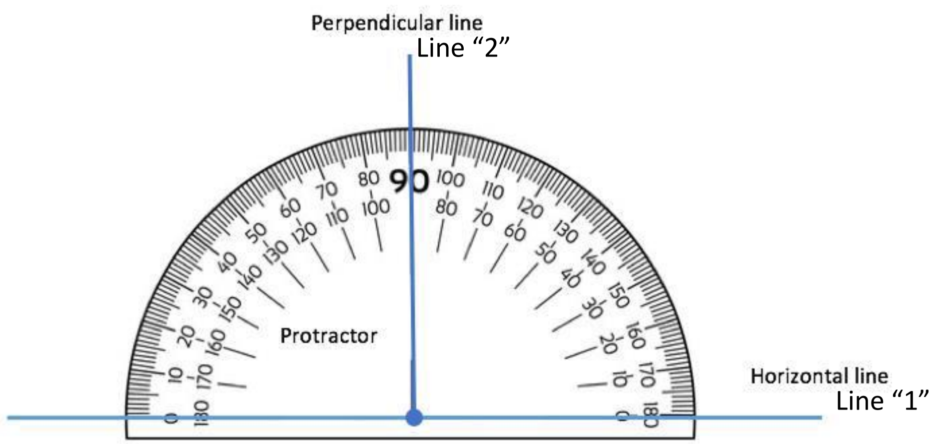


Figure 5. Protractor with horizontal line “1” and perpendicular line “2” drawn.

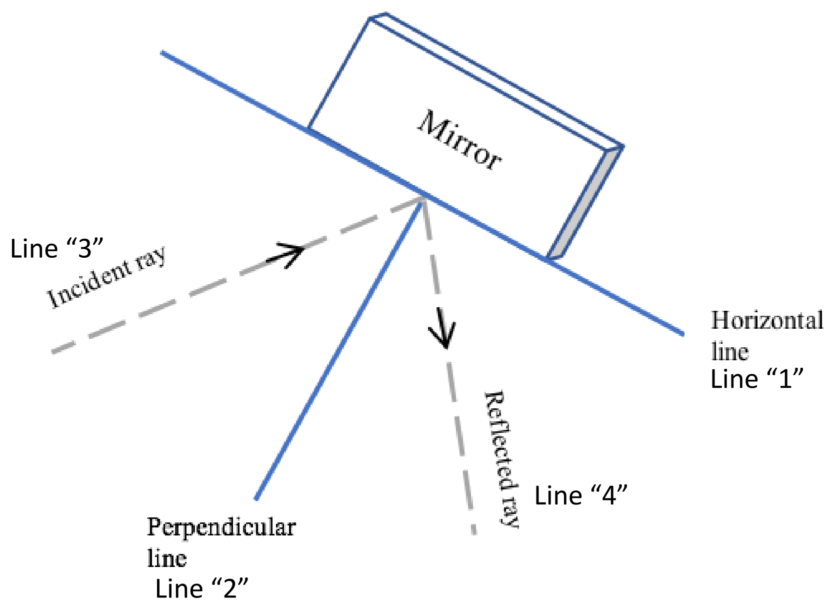


Figure 6. Experimental set-up with mirror placed on horizontal line “1” and perpendicular line “2”, incident ray line “3”, and reflected ray line “4” drawn.

3.1.5. Results

Angle of incidence (θ_i)	15°	30°	45°		
Angle of reflection (θ_r)					

3.1.6. Post-Experiment Questions

1. During this investigation, how did the angle of reflection vary with the angle of incidence?

2. Did your Results follow the law of reflection? Why or why not?

3. Were there any challenging aspects of this experiment?

3.2. Part IIa. Light and Refraction

3.2.1. *Summary*

This experiment aims to show how light bends as it travels from one medium to another. The media in this experiment are water, air, and glass.

3.2.2. *Pre-Experiment Questions*

1. How does light change as it passes through different media, like from air to water?

2. What is refraction? How does this change the appearance of objects?

3.2.3. *Materials*

- 1 pencil
- 1 empty glass
- Water

3.2.4. Procedure (2-4 students per group)

1. Place the pencil in the empty glass, letting the top of the pencil rest against the side of the glass.
2. Observe the shape of the pencil from the side and top of the glass. Record your observations.
3. Add water to the glass, about half-full.
4. Observe the shape of the pencil from the side and top of the glass.
5. Record your observations in the table in Results.

3.2.5. Results

	Observations from side (sketch or explain)	Observations from top (sketch or explain)
Pencil in empty glass		
Pencil in glass half-filled with water		

3.2.6. *Post-Experiment Questions*

1. What is different about the pencils you observe? How do you explain the differences you observe?

2. Try sketching the situation you observe with the glass half-filled with water and the pencil. Include how the ray of light passes through the glass and water and how this impacts what you observe.

3.3. Part IIb. Snell's Law

3.3.1. *Summary*

This experiment will guide students to use Snell's Law through refraction of light via different media including air and sugar water.

3.3.2. Pre-Experiment Questions

1. What is Snell's Law? Describe in words and using an equation.

2. Sketch an incident and refracted ray of light passing through two media of different refractive indices. Include angles of incidence and refraction in your sketch.

3.3.3. Materials

- Laser pointer (or cell phone light or light source with collimation)
- Cardboard pieces/thin book/piece of wood to place laser pointer on
- Tape

- Protractor
- Paper
- Square plastic or glass container (try to find a container that has reduced curvature)
- Water (enough to fill container at least halfway full)
- Sugar (enough to make sugar-water solution that is 4 parts water to 1 part sugar) (note: if you do not have sugar, canola or other oil can be substituted for sugar-water)

3.3.4. Procedure (2-4 students per group)

1. Draw a horizontal line the length of your square clear container on your piece of paper. This line will represent the interface between your media, so you can label it "interface".
2. Draw a perpendicular line in the middle of this horizontal line of about the same length. This line is normal to your interface. You can see from the two lines you have drawn that you should now have four quadrants: upper right and left and lower right and left.
3. In the upper right quadrant, measure a 30-degree angle from your perpendicular line (i.e., the line normal to your interface). Label this angle as "refracted angle θ_2".
4. Place the clear container so that its edge lines up with the horizontal line labelled "interface" (see Figure 7).
5. Lay the laser pointer flat on a few cardboard pieces (or thin book or piece of wood) and secure the laser pointer with a piece of tape. This mount will help elevate the laser pointer a bit and ensure it does not move too much during the rest of the experiment. Note: If you do not have a laser pointer, you may need to collimate your cell phone light or light source with a piece of cardboard and a small hole (i.e., place the cardboard with small hole between the light source and the container to create a beam of light).
6. Using the laser pointer on its mount from the lower left quadrant of your grid (in air and outside of the container), direct the laser light so that it passes directly through the container at the vertex of the interface and normal lines and travels along the 30-degree angle line you have drawn on your paper (this line should now be under the container but visible). You will likely need your partners to

help get your laser light aligned. Ask your partners to observe the light from above to accurately see the laser light's position.

7. Mark the path of the laser light before entering the container with a few dots. You can do this by noting where the pen/pencil hits the laser light and making a dot there. Label this angle as "no liquid θ_1". This is your incident angle. Do not move any part of the experimental set-up as you proceed to the next step.
8. Mix 1 part sugar to 4 parts water to create enough solution that will at least fill your container halfway full. After the sugar-water is well mixed, add it carefully to the container. <u>Note:</u> if you do not have sugar, you can also use canola or other oil instead of sugar-water for this step.
9. Repeat steps 6 and 7 but instead label the angle as "liquid θ_1". Notice if you need to re-align your laser position to get it to line up with the 30-degree mark under your container.
10. Remove the paper from underneath your container. Connect the dots for your two angles labelled "no liquid" and "liquid" into two lines that pass through the vertex of the interface and normal line.
11. Measure these angles with your protractor and record these values in the table in Results.
12. Calculate the refractive index of the second medium (the empty and filled container) using Snell's Law. The refractive index for air, which is very close to 1, is given.

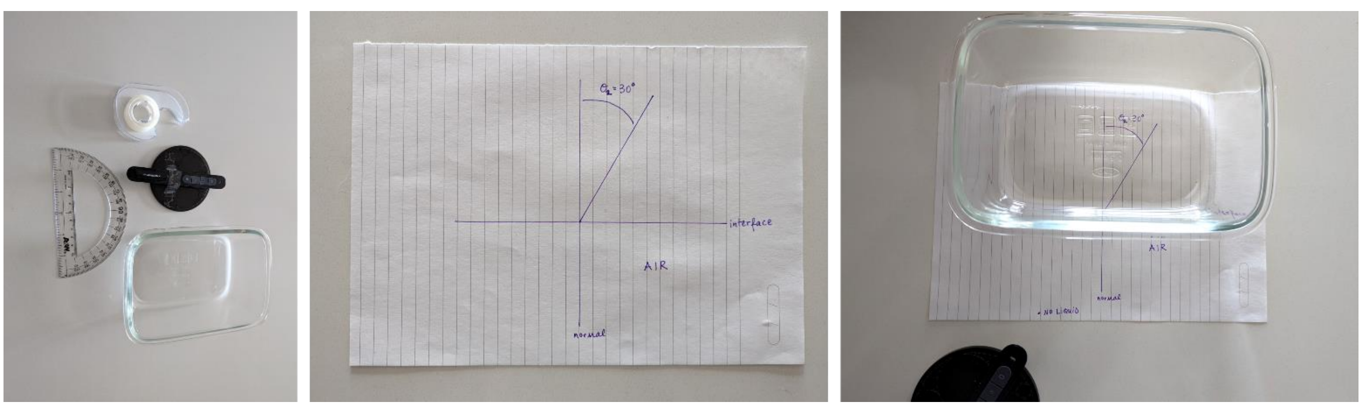


Figure 7. Experimental set-up. Supplies (left) showing laser and mount. Drawing before placing container (middle). Set-up after placing container lined up with interface line (right).

3.3.5. Results

Second medium	Incident angle, θ_1	Refracted angle, θ_2	Refractive index, air	Refractive index, second medium
No liquid/air		30°	1	
Sugar-water		30°	1	

3.3.6. Post-Experiment Questions

1. How did the incident angle change as the medium in the container changed? Comment on if the incident angle was more or less than the refracted angle in both cases.

    a. Extension question: What does it mean if the incident and refracted angles are the same? Consider Snell's Law.

b. Extension question: If your incident and refracted angles in the case in which there was no liquid in the container were significantly different, comment on why you think this was observed.

2. What was the refractive index you measured for the sugar-water?

3. Were there any challenging aspects of this experiment?

3.4. Part IIc. Light and the Rainbow

3.4.1. Summary

This experiment aims to show how refraction bends the visible light that is passed through a “prism” into its basic colors. The experiment also shows that white light is a mixture of many colors, namely Red, Orange, Yellow, Green, Blue, Indigo and Violet.

3.4.2. Pre-Experiment Questions

1. How are colors made visible from white light? Be sure to use the word "refraction" or "refracts" in your answer.

2. What are examples of refraction in your life?

3.4.3. Materials

- 1 piece of cardboard or thick paper that will not allow light to pass through
- Scissors
- 1 clear glass half-filled with water (you can also use a prism)
- Sunlight (or a bright lamp with white light)
- Paper

3.4.4. Procedure (2-4 students per group)

1. Cut a small hole in the cardboard or thick paper. The hole should just be large enough for a pencil to fit through it.
2. Place the plain paper on the floor or ground.

3. (Student 1) Angle the piece of cardboard with the hole in it so that light shines through onto the plain paper on the ground. Typically, the cardboard casts a shadow on the white paper, and you can see the light through the hole on the paper.
4. (Student 2) Hold the glass with water just behind the hole in the cardboard so that the light must travel through the water before hitting the piece of paper. If you have a prism, you can use it instead of the glass with water. The set-up for this experiment is shown in Figure 8.
5. Observe the results on the piece of paper.
6. Try moving the piece of paper closer and farther away from the glass and observe what happens.
7. Try rotating or changing the position of the water glass and carboard and observe what happens.

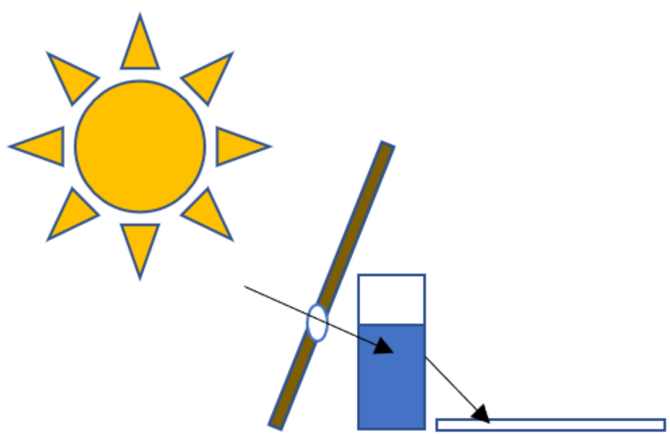


Figure 8. Experimental set-up. Cardboard with hole is angled so that light passes through the hole and is directed onto the glass with water. You may need to slightly change the positions of your cardboard, water glass, and paper to see the light hitting the piece of paper.

3.4.5. *Post-Experiment Questions*

1. What did you observe on the piece of paper after holding up the glass of water to the light? If you saw colors, which colors did you observe?

    a. Extension Question: If you observe the colors of the rainbow in order, can you speculate on which color travels the slowest and fastest? Which color has the highest refractive index, and which has the lowest refractive index? You may need to refer back to the Background on Main Topics.

    b. Extension Question: Did anything change as you moved the paper closer or farther away from the glass or rotated the position of the water glass and cardboard?

2. Draw a diagram that explains what you observe that includes the incoming white light and outgoing light. Explain also in words what you are observing, including why you use a piece of cardboard with a hole in it and a glass filled with water.

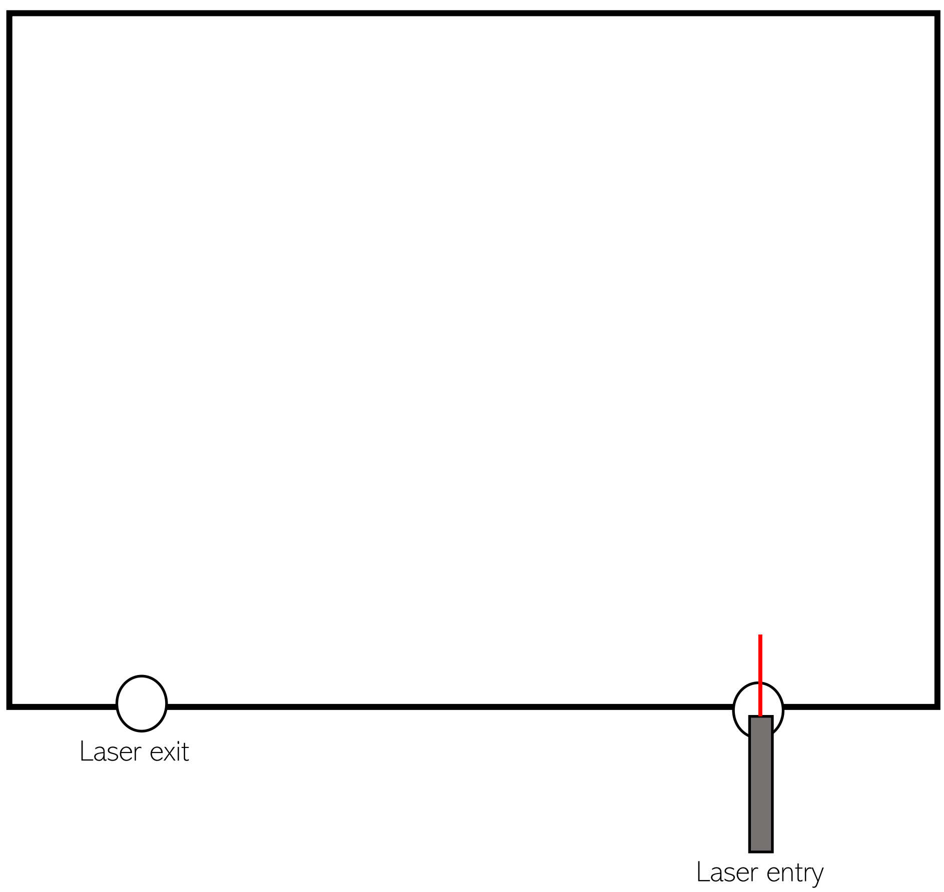
3. Speculate what would happen if you added a second glass with water to the configuration you currently have by directing the light from the first glass onto the second glass and the onto the paper. You may want to sketch out how the light will bend moving through the second glass with water (i.e., second prism). You can also try this with a second glass with water!

4. How would the use of a laser pointer change the outcome of this experiment?

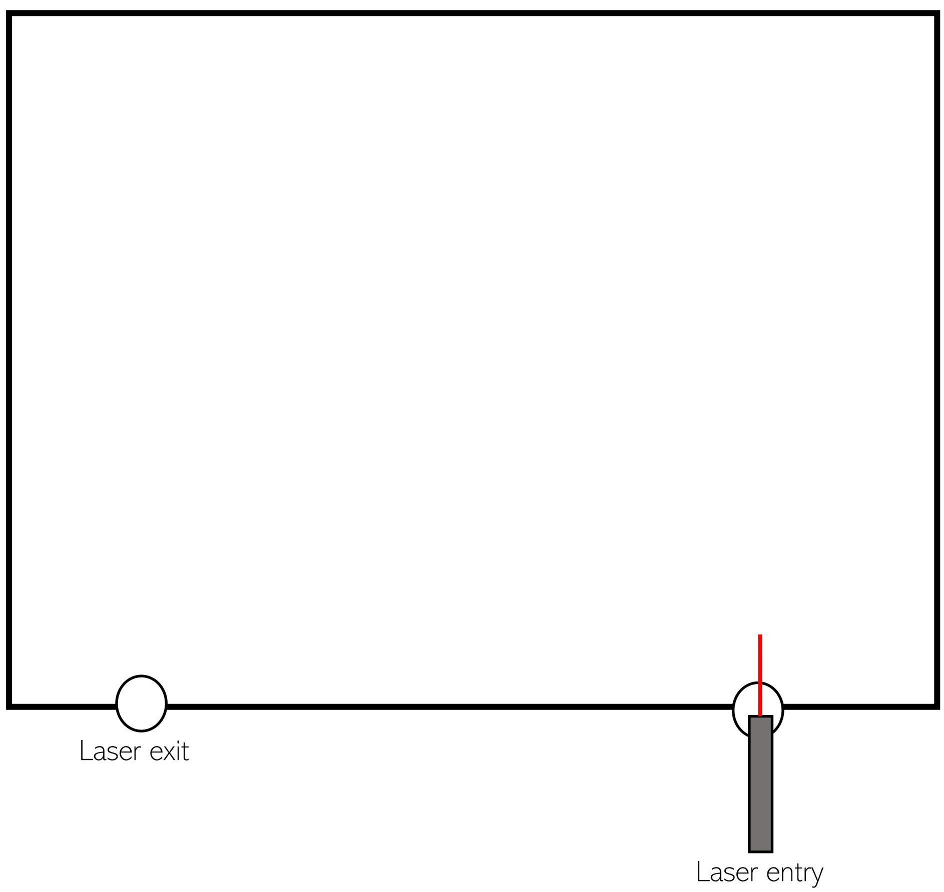
4. Design Challenge: Directing Light

4.1. The Challenge

<u>Challenge 1:</u> You have a laser pointer and a cardboard box with two holes in it (assume the holes are at the same height on the sides of the box and are roughly the same shape and size). The laser pointer is directed into one hole of the box. Using what you know about reflection, fill in the sketch below by drawing where you would place mirrors for the laser light to be directed out of the second hole of the box. Remember that you may need to use a protractor to prove if your design will work. If you have the supplies for this challenge, you can test whether your design worked!



Challenge 2: You have a laser pointer and a cardboard box with two holes in it (assume the holes are at the same height on the sides of the box and are roughly the same shape and size). The laser pointer is directed into one hole of the box. Using what you know about reflection and refraction, fill in the sketch below by drawing where you would place mirrors and prisms for the laser light to be directed out of the second hole of the box. You must use at least one prism in your design, and you can approximate the exit point of the light from the prism based on what you learned about light bending. If you have the supplies for this challenge, you can test whether your design worked!



4.2. Post-Design Questions

1. Explain the concepts you used from this lab kit to complete these design challenges.

2. How do you feel about the results of your design methods?

3. Did you try several methods to complete these challenges? Which method had the most success? What characteristics made it have the most success?

4. How would you change your designs after viewing yours and your classmates' results?

5. What was challenging about completing these design challenges? How did you work through those moments of confusion or frustration?

6. What did you enjoy most about completing these design challenges?

5. Additional Resources

5.1. Phet Simulation

If you have a computer, the Phet simulation (https://phet.colorado.edu/en/simulations/bending-light) can be used to replace the hands-on experiments above if equipment is not available or in addition to the hands-on experiments.

There is also a video describing how to use the Phet simulation tool: https://www.youtube.com/watch?v=uTX0Rnnf1AQ.