PHOTON

and

PHOTON 2

EXPLORATIONS in OPTICS

The PHOTON/PHOTON2 Explorations are adapted from favorite simple and low-cost experiments and demonstrations shared by the participants of PHOTON and PHOTON2. Projects PHOTON (DUE#0053284) and PHOTON2 (DUE #0302528) were supported in part by grants from the Advanced Technological Education program of the National Science Foundation to the New England Board of Higher Education (NEBHE). For further information, contact Fenna Hanes, fhanes@nebhe.org.

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1. Exploring Light Spectra

CAUTION! Do not look into the laser cavity or at any reflections of the laser from shiny surfaces. Do not look into the sun!

Question: Can you tell what wavelengths (colors) are produced by a light source by just looking at the light?

Materials:

- Incandescent bulb with various colored filters
- Laser pointer
- Other sources of light: LEDs on electronic equipment, fluorescent and energy saving fluorescent bulbs, outdoor street lighting, a flame, illuminated signs…
- Home made spectrometer: cardboard tube, diffraction grating from the OSA Optics Discovery Kit (or piece of a CD with the shiny label removed), and aluminum foil (See Procedure, below.)

Background:

Recognizing colors is one of the first things you learned to do as a child. Isaac Newton used a prism to separate sunlight (or "white" light) into the colors of the rainbow: Red, Orange, Yellow, Green, Blue, Violet. He showed that these colors cannot be further separated; that is, they are fundamental colors of light. The colors of visible light are a part of the electromagnetic spectrum, which also includes radio waves, micro waves, infrared and ultraviolet light, x rays and gamma rays. Each color in the visible spectrum has a different wavelength.

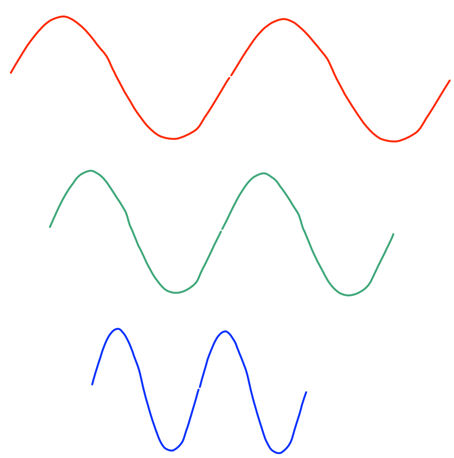


Figure 1 - Wavelengths of red (longest), green, and violet (shortest) light

Often the color that you see contains several of the fundamental colors of light. For example, a television screen or computer monitor displays only three colors. The combination of varying amounts of the three colors produces all the colors you see on the screen. You can see the tiny color pixels if you look at the screen with a magnifier.

In this lab you will examine the colors radiated by several different sources of light. When the colors are displayed in order of wavelength we call it the *spectrum* of the light source. A rainbow is the spectrum of sunlight! Like a prism, the diffraction grating in your optics kit can break light into a spectrum of wavelengths (colors) so you can see the colors that are radiated by a source of light. To get the clearest spectra, you first need to construct a spectroscope. You can see spectra using just the grating alone, but the tube blocks out overlapping spectra from other sources in the room

Procedure:

1. Making the spectroscope:

- Cover one end of a cardboard tube (a toilet paper tube is fine) with aluminum foil. Hold the foil in place with a rubber band. (See Figure 2.)
- Poke a small hole (about 1-2 mm) or slit in the center of the foil with the point of a pencil.

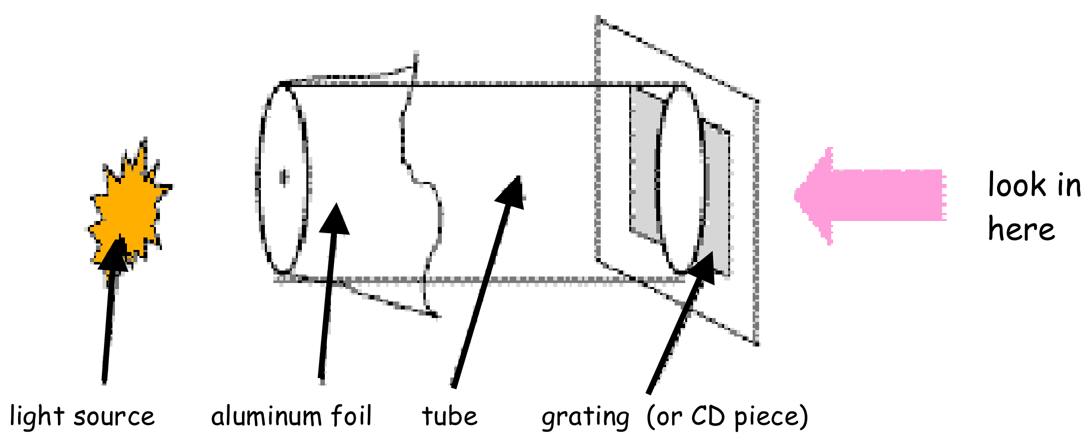


Figure 2 - The cardboard tube spectroscope

- With the diffraction grating: Place the diffraction grating slide against the end of the tube opposite the slit. Place the hole near the light source. Be careful if it is a hot light bulb. Put your eye very near the grating and look through the grating and the hole.

- <u>With the CD:</u> If you don't have a diffraction grating you can use an old CD. Remove the label by scratching the label side with a knife or scissors. Firmly stick wide tape, such as packing tape, onto the label over the scratch and then pull the tape sharply away. The label should peel off. (Some labels are easier to remove than others.) With scissors, cut a circle from the CD and tape it to the end of the tube, opposite the hole.

2. Observing sources:

- Look through the diffraction grating with the pinhole pointed toward the source. You will see a bright spot in the center which will have the same color as the source itself. On either side, you will see one or more "spectra"- a full rainbow for a source like a light bulb and individual lines for sources like street lights or energy saving fluorescent bulbs. You may have to look quite a bit to the side of the central spot to see the spectra. Focus on one of these spectra, which will include some or all of the colors of the visible spectrum. For an example of what you will see, look at Figure 3.
- Find at least five different light sources. (Hint: anything that glows is fair game, for example, light bulbs and LEDs, a stove unit, candle flame, street lights, etc.) A colored light, such as a green night light or holiday bulb, would be an excellent choice.
- If you have a laser pointer, include it as one of your sources. However, DO NOT look directly into the laser with your spectroscope. Shine the laser on a piece of white paper and look at the light reflected from the paper. You can view the spectrum of sunlight the same way, by looking at sunlight reflected from white paper.

Observations:

Fill in the data table for each source. List the type of light that you were observing and a description of the spectrum you see through the spectrometer what colors are present and which of the colors are brighter/dimmer. Then answer the following questions:

Do the spectra of the colored sources contain only the color of the source? That is, if you looked at a red light bulb, did it show other colors in the spectrum or just red? Do some spectra have more colors than others?

Conclusion:

Can you tell what colors are in a light source by looking at it with your unaided eye?

DATA TABLE

Type of light source	Colors you saw in the spectrum

SAMPLE SPECTRUM

To see additional spectra, plus photos of the "homemade spectroscope" used in this lab, visit www.lasertechonline.org/optics/optics_index.html. Figure 3 shows the photograph of the spectrum of an energy saving fluorescent bulb, taken through an actual toilet-paper-tube spectroscope. The grating used shows two spectra on either side of the center image. Lines are formed because the aluminum foil was cut with a slit rather than a round hole. If you look carefully, you will see five colors in the spectrum: red (very bright), orange (very faint- look at the spectrum on the far right), green, blue-green and blue-violet.

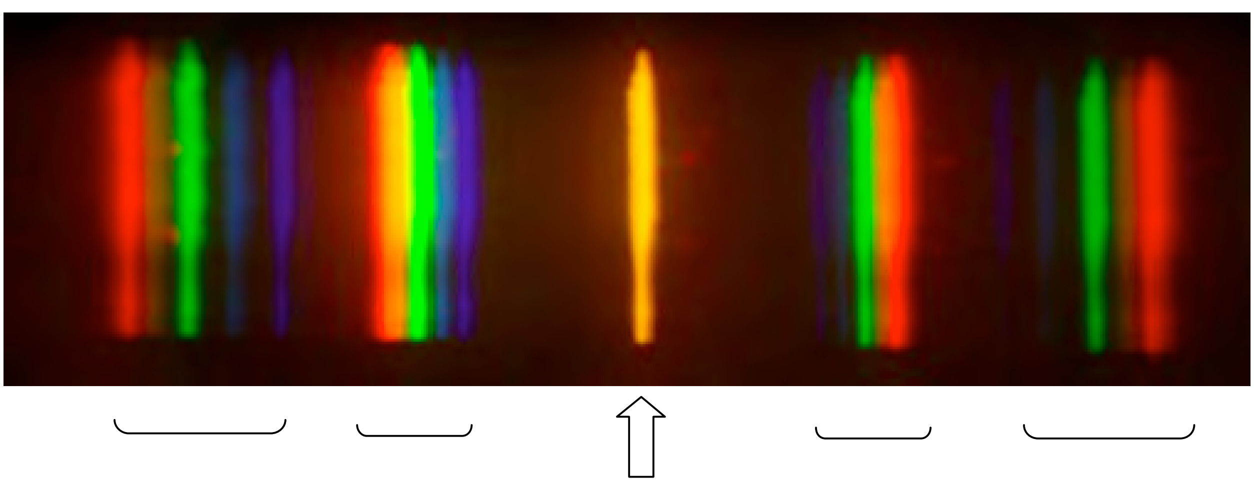


Figure 3 - Spectrum of an energy saving fluorescent bulb. The arrow shows the center light, which is the color of the bulb. There are two spectra on either side. You may only see one spectrum on either side- it depends on the grating you use.

2. What Color is a ...?

Question: **Can your eyes be fooled by the color of a light source?**

Materials:

- An orange, lime, or tomato- any piece of fruit that is one solid color. Or you can also print a solid color circle about 5 cm in diameter using a color printer.
- Colored LED flashlight or regular flashlight with a transparent color filter over the end. The color should not be the same as the fruit.

Background:

Recognizing colors is one of the first things toddlers learn to do. But does an object always appear to be the same color? What makes an orange look orange or a tomato look red? Here is a hint: When light strikes an object, it can be reflected, transmitted through the object, absorbed by the object, or scattered by tiny "granularities" in the object. When headlights hit fog, for example, some light passes through the fog (you can see the light of oncoming cars), some is scattered (the fog "lights up" over a wide area), some is absorbed by the water droplets, and some is reflected back toward the driver. All of these effects are wavelength dependent.

In order to see the color of an object, that wavelength needs to be reflected back toward your eyes. What happens if the illumination source doesn't have include the necessary wavelength(s)? Let's find out…

Procedure:

1. Turn out all the lights to make the room as dark as possible. If you can't make the room dark enough, you can place the object in a large carton. Cut a hole in the carton top so you can shine the light in and see the object.
2. Now shine the colored light on the object. If you have an orange or tomato, for example, use blue or green light. Try different colors, if you have them, and different objects as well.

Observations:

For each object and each illumination type, answer the following questions. Be sure to say what the object was and what type of illumination you used.

1. What color is the object under "white" light (sunlight)?
2. What color did the object appear under this type of illumination?
3. Why did the object appear to be the color you saw?

Conclusions And Applications:

1. What is necessary for you to be able to see the "true color" of an object?
2. Explain the photograph in Figure 1. The two scenes contain the same color objects- the towels, chairs, desks and even the walls are identical on both sides. What occupations would need to know about how the colors we see are affected by lighting?

Figure 1 - Photograph taken at the Southern California Lighting Technology Center in Irwindale, CA.

3. Exploring Pinhole Images

Questions: **How can you make an image (picture) with just a cardboard box and a pinhole? How can you predict the size of the picture?**

Materials:

- Large carton or box with the bottom removed
- Aluminum foil
- Needle, tape
- Translucent paper, like vellum paper (optional)

Background:

A pinhole camera consists of a closed light-tight box with a small pinhole centered on one end. The pinhole is located where you might expect a lens to be in a regular camera. Like a lens, the pinhole can form an image on a screen.

As you can see in Figure 1, rays of light from the top of the lamp pass through the pinhole and strike a small area on the end of the box. The rays from the bottom of the lamp do not overlap the rays from the top because of the small size of the pinhole. Thus, an image of the lamp is formed on the back of the box.

If the hole is too large, the overlapping rays will form a blurry image, or no image at all. To use the box as a camera, film is placed at the image location. Exposure times are very long (up to several hours). In this exploration, you will use a box that is open at the bottom so you can look in and see the image.

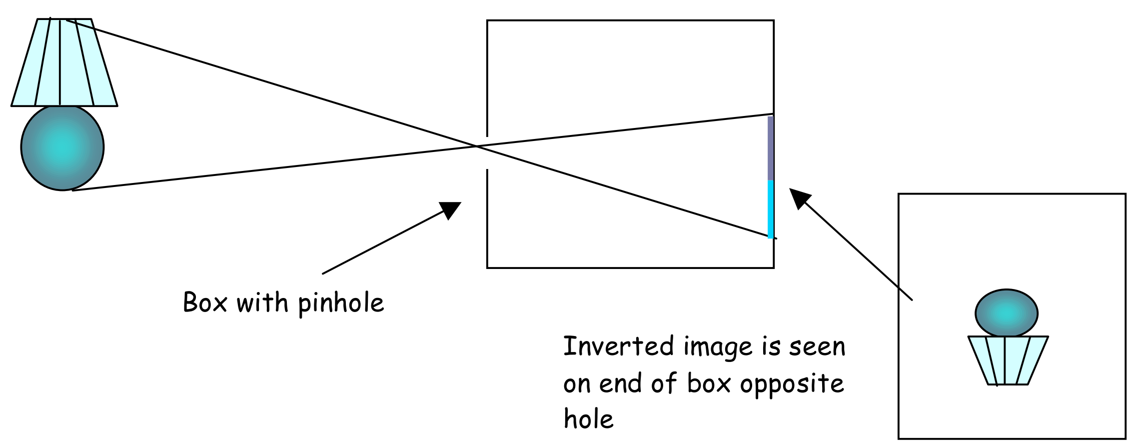


Figure 1 - The pinhole camera viewer

Procedure:

1. Cut a hole approximately 5 cm square in the center of one end of the box. Be sure the edges and corners of the box will not let in any stray light. (You can cover the ends and corners with black electrical tape, if necessary.)
2. To make the pinhole, stack 5-6 pieces of aluminum foil cut slightly larger than the hole in the box. Pierce the stack with a needle. The inner foil pieces should have neat pinholes, with clean edges. Tape one of these foil pieces over the hole in the box, centering the pinhole.
3. Aim the pinhole toward a light source and look up through the open bottom of the box to observe the image on the end opposite the pinhole. A lamp in a darkened room makes a good object. It may be easier to see the image if you tape a piece of white paper in the box on the side where the image forms.

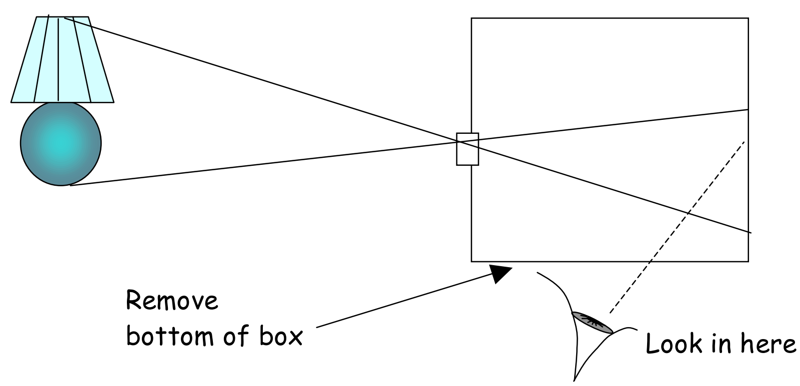


Figure 2 - Using the pinhole viewer

4. (Optional) If you have translucent paper, you can leave the bottom of the box in place and cut a hole in the back of the box. Cover the hole with the paper and use it as a screen.

Observations:

What did you use for an object? Describe the image you saw- was it upright or inverted? Sharp or blurred? Describe any other features about the image that you noticed.

Conclusion:

What can you do to create a larger image? (Hint: look at the triangles in Figure 1.) Why would a pinhole viewer be a good way to look at an eclipse of the sun?

Teacher's note: The PHOTON lab manual has directions for creating and using a pinhole camera to make permanent pinhole images using photographic paper.

4. Exploring Reflection from Transparent Objects

Question: How can you see a transparent object?

Materials:

- Two beakers with level markings – one larger and one smaller, sized so that the smaller beaker fits inside the larger beaker.
- Vegetable or mineral oil (enough to fill the larger beaker).

Background:

In order to see something light must go from that object to your eyes. A glowing object like a light bulb emits light that you can see, but other objects must reflect light for you to see them.

Whenever light travels from one medium to another (for example, air to glass or glass to water) part of the light is reflected and part of the light is transmitted into the second material. The amount of light reflected depends on the *index of refraction* of the two materials.

The index of refraction of a material is the ratio of the speed of light in a vacuum to the speed of light in the material. For example, glass has an index of refraction of 1.5, which means that light travels 1.5 times faster in a vacuum than in glass. The symbol for index of refraction is n, and we distinguish the index of refraction of the first material from that of the second by using the subscripts "1" and "2". So the index of refraction of the first material is n_1 and the index of refraction of the second material is n_2.

When light travels from a medium having one index of refraction to a material having a different index of refraction (Figure 1), some of the light is reflected at the surface. This is known as Fresnel reflection. When light goes from air to glass or from glass to air, about 4% of the light is reflected at the surface. The larger the difference in index of refraction, the larger the amount of light reflected. This reflection allows us to see things that are considered to be transparent, like window glass.

What if the piece of glass in Figure 1 is not surrounded by air, but rather some material that has the same index of refraction as the glass? Would we still be able to see it? Let's explore…

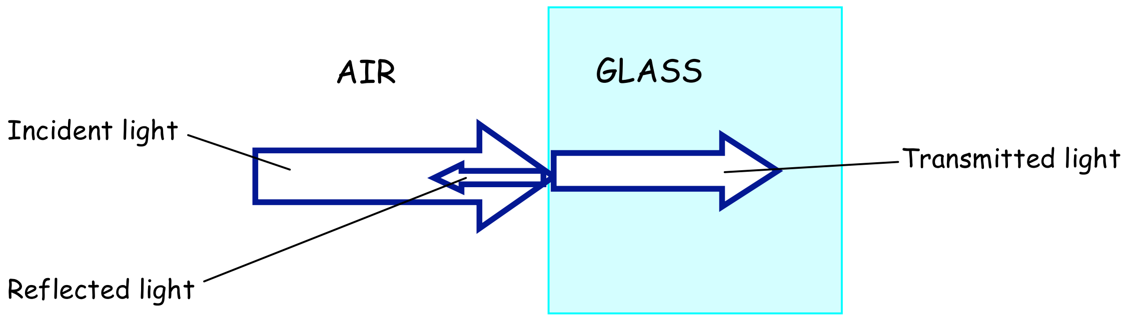


Figure 1 – Reflection at an Air-Glass Interface. Additional light will be reflected at the second surface, but this is not shown.

Procedure:

1. Place the smaller beaker in the larger beaker.

   Observation 1: Can you see the smaller beaker?

   Conclusion 1: Why can you see the smaller beaker?

2. With the smaller beaker still inside the larger beaker, carefully pour the oil into the smaller beaker only until it is full (see Figure 2).

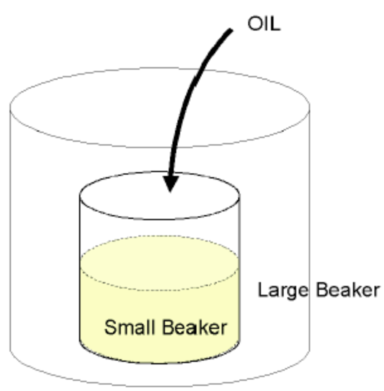


Figure 2 – Smaller beaker inside larger beaker

   Observation 2: Can you see the smaller beaker?

   Conclusion 2: Why can you see the smaller beaker?

3. Now continue pouring the oil into the smaller beaker so that it overflows into the larger beaker. Continue pouring until the smaller beaker is completely submerged in oil.

   Observation 3: Can you see the smaller beaker?

   Conclusion 3: Why can't you see the smaller beaker anymore?

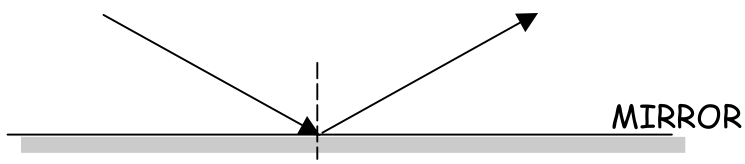
5. Hit The Target

Question: Can you arrange a mirror so that light will reflect from it and hit a target? What do you need to know about light and mirrors?

Materials:
You don't have to use all of these materials, just use what you need.

- 1 low power helium neon laser
- 3 mirrors
- 3 protractors
- String
- Masking tape
- Meter stick
- Target (see below)

Background: When light strikes a mirrored surface the angle of reflection equals the angle of incidence. In this challenge you will use this law to help you place mirrors so that a laser beam hits a target.



The Challenge:

Round 1: You have 10 minutes to hit the target using ONE mirror.
Round 2: You have 15 minutes to hit the target using TWO mirrors.
Round 3: You have 20 minutes to hit the target using THREE mirrors.
⇨In each round, the highest score will be recorded.

Rules:

1. The laser and target will be set up for you by the instructor or assistant. *You may not move either laser or target.*

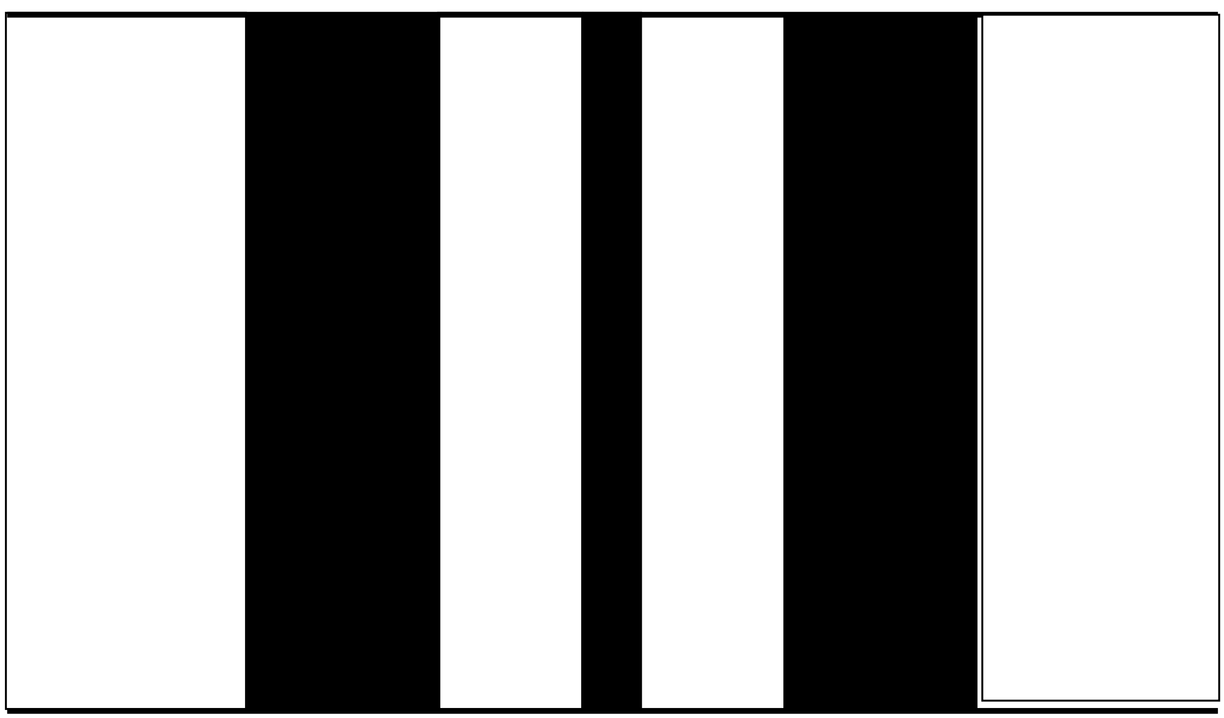
2. **The laser must be kept turned off until you have set up the mirrors!** When you're ready, the instructor or assistant at your table will turn on the laser. *You may not move any mirrors while the laser is on.*

3. If you don't get 100 points on your first try, the instructor or assistant will turn the laser off and you may move the mirror(s) and try again. You can keep trying until time is up for that round.

4. If the laser falls on a line between regions of the target, you will be awarded the average of the points on either side.

5. The mirrors must be at least 25 cm from the laser and from each other.

Sample Target- Cut out and mount on cardboard



6. Exploring Refraction (Jello® Optics)

CAUTION! Do not look into the laser cavity or at any reflections of the laser from shiny surfaces.

Question: **How do lenses change the path of light?**

Materials:

- Jello® Jigglers
- Toothpicks for cutting
- Round cookie cutter, or strips cut from a plastic folder for cutting
- Light source - focusable flashlight, laser or ray box if available

Note on Jello®: The recipe for Jigglers is on the Jello® brand package. Yellow (lemon) works well. It is sticky however, so if that is an objection, plain gelatin (such as Knox® brand) may be used. A very stiff gel is needed- use one third the usual amount of water for each packet of gelatin. Use hot (boiling) water only and stir very well. Pour into pans, allowing the gelatin to be 2-3 cm thick. Place in the refrigerator. (However, it will gel at room temperature.)

Note on light sources: Laser pointers are best. If there is a problem obtaining enough laser pointers, or if safety is an issue, a flashlight can be used for most experiments. A physics "ray box," which is a special light source that produces one to five collimated "rays" of light, works best.

Background:

In a vacuum, light travels at 3×10^8 meters/second or 186,000 miles per second. This is the fastest light (or anything) can move. When light enters a transparent medium, it slows down and its wavelength (the distance between wave crests) shortens. Because of this, a beam light traveling from one medium to another may change direction; the beam bends as it enters the new medium.

Think about a marching band, in neat even rows, marching along a paved surface bordered by deep mud. The marchers can walk faster on the pavement than in the mud, where their feet sink in the ooze. If the band is moving toward the muddy edge of the pavement, when the marchers at the end of each row reach the mud, they will slow down. (See Figure 1.) The result is that the rows will bend.

Waves behave in a similar fashion. If you think of the heads of the marchers lined up along the crests of waves, you can see how waves will bend when they go from a medium where they travel fast to a medium where they move more slowly.

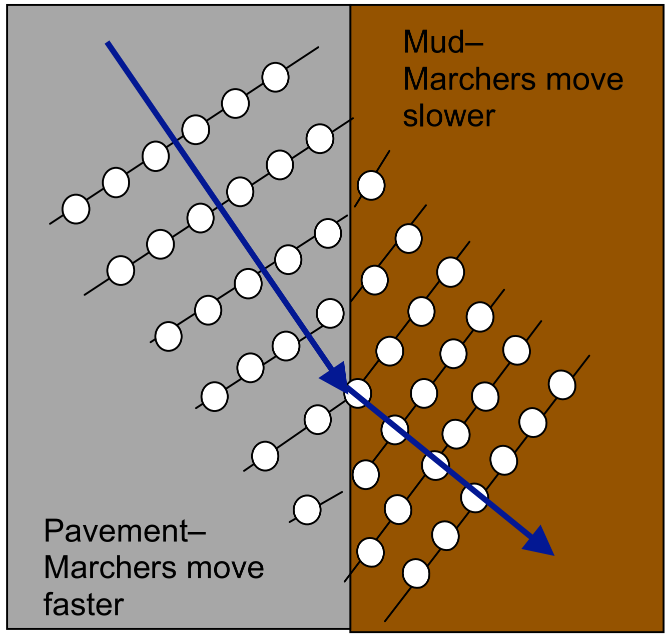


Figure 1 - Bending of rows of marchers hitting the interface between hard pavement and soft mud.

The bending of waves as they go from one medium to another is called refraction. Refraction of light explains many things you see around you every day, such as the apparent bending of a spoon when it is partially submerged in water and how lenses, including those in eyeglasses, work.

When we measure the angles, we speak of the angle of incidence and the angle of refraction. Incident light is light that is striking the surface or the medium, and refracted light is the light inside the medium. The angles are measured from a line drawn at 90° to the surface (Figure 2).

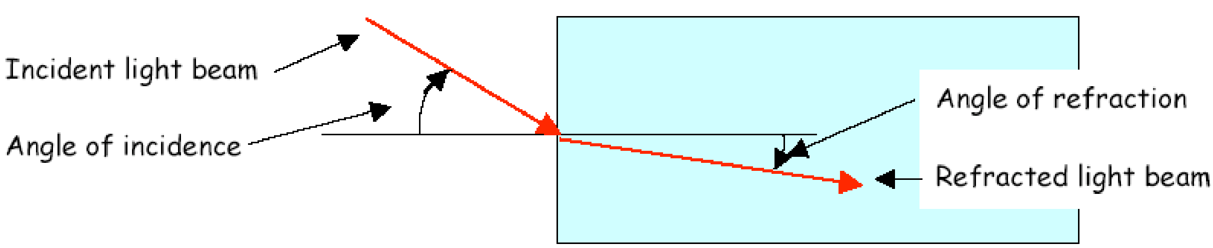


Figure 2 - Angles of incidence and refraction

Activity 1: Refraction (works best with a laser or ray box, using one ray)

Cut a gelatin rectangle about 3 cm x 4 cm. The size is not important, but the edges must be very straight and smooth. On a piece of paper, draw two long lines that cross at a 90° angle. Draw three more lines showing angles of incidence of 30° 45° and 60° as shown in Figure 3.

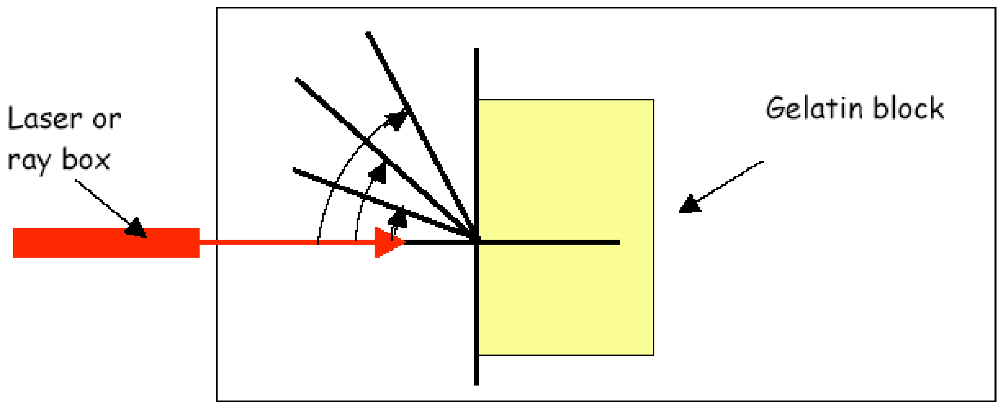


Figure 3 - Jello® block and paper with lines as seen from above

Place the straightest edge of the gelatin block along the vertical line on the paper. Now use the laser pointer or one ray from a ray box and shine it directly into the edge of the gelatin block along the horizontal line, so it strikes the edge of the block at 90°. (Note that this is called a "0° angle of incidence.")

Observation 1: Does the beam of light bend when it goes from the air straight into the gelatin? When it goes from the gelatin back into the air?

Use the laser pointer or one ray from a ray box and shine the beam along each of the other lines you have drawn (angles of incidence of 30°, 45° and 60°). Each time, notice where the beam comes out of the block on the other side. Notice which way the beam bends as it enters the block of gelatin. (See Figure 4.)

Observation 2: Does the beam bend toward the horizontal line or away from the horizontal line when it enters the gelatin block? As the angle of incidence increases, does the beam bend more, less, or the same amount?

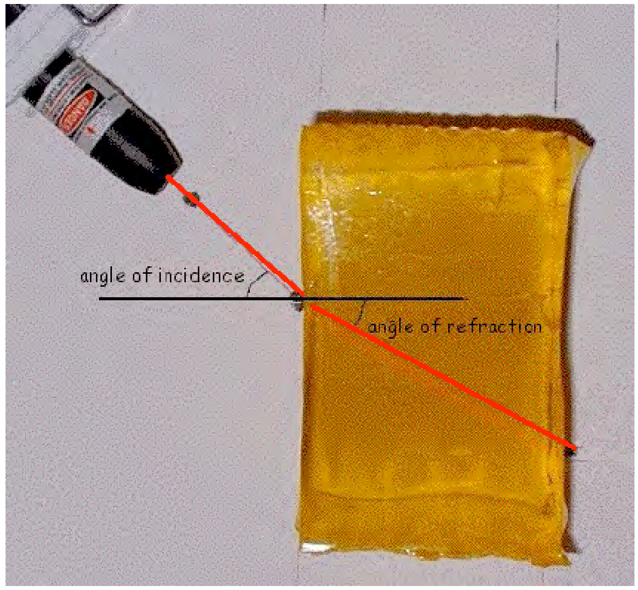


Figure 4 - Photograph of the gelatin block and laser. The laser beam is highlighted so that it is easier to see.

Activity 2: Lenses

To cut gelatin "lenses" into the "cookie" shapes shown in Figure 5 you will need to use the circle cookie cutter and a flat block of gelatin. Notice that the curved surfaces are actually parts of circles. Practice until you can make shapes with smooth sides that look like the ones in Figure 5. Carefully cut lenses from a gelatin block, keeping the edges as smooth as possible.

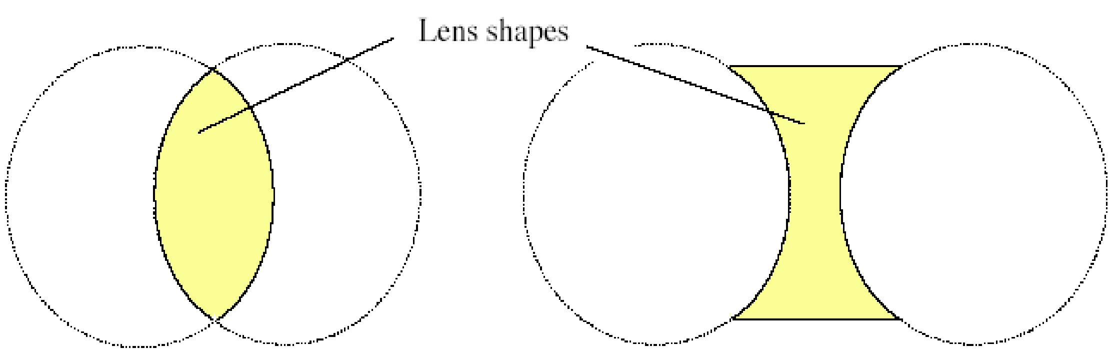


Figure 5 - Lens shapes cut of a gelatin block using a circle cookie cutter. The circles show the position of the cookie cutter. The yellow shaded shapes are the "lenses" that you will use for this experiment.

Place one of the lenses on a piece of paper. Shine the ray box rays through one edge of the lens and observe how the light behaves as it passes through the lens (Figure 6). You can use a flashlight focused to a collimated beam instead of a ray box. If you use the laser pointer, shine it in along one of the arrows shown in Figure 6 and trace the path of the ray on the other side with a pencil. Move to another (parallel) position and repeat. Draw at least 5 rays and see what happens on the other side of the lens.

Repeat with the other lens.

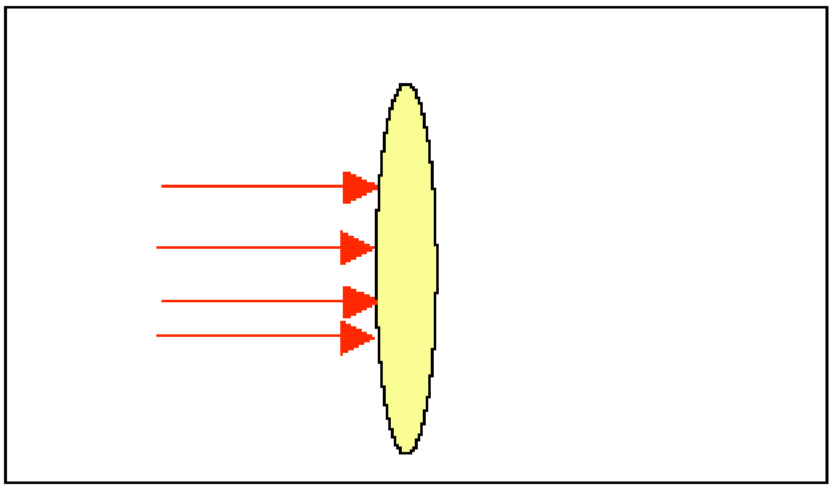


Figure 6 - What does the lens do to the rays of light?

Observation 3: What does the lens on the left in Figure 5 (called a converging lens) do to the light?

Observation 4: What does the lens on the right in Figure 5 (called a diverging lens) do to the light?

Conclusion:

How does refraction of light explain how a lens works?

7. Exploring Lenses - The Magic Lens

CAUTION! Do not look into the laser cavity or at any reflections of the laser from shiny surfaces.

Question: **Can you make a lens out of air and use it in water? How will it behave differently from a glass lens used in air?**

Materials:
- Two watch glasses (these are used in a chemistry laboratory)
- Tube of silicone caulk, like bathroom caulk
- Fish tank large enough to hold lens
- Focusable flashlight (like a Maglite®) or laser beam or optics ray box
- Clamps to hold the lens in place in the tank (optional)

Background:

A lens works by refraction, the bending of light as it goes from one material into another. A lens made of glass that is thicker in the center than at the edges will cause light to bend so that it passes through a point on the other side. We call this type of lens a converging lens. Figure 1 shows how the light bends as it enters the glass from the air and then leaves the glass to return to the air. Each time, light bends toward the center line, called the "optical axis." The point where the light rays meet is called the focal point of the lens.

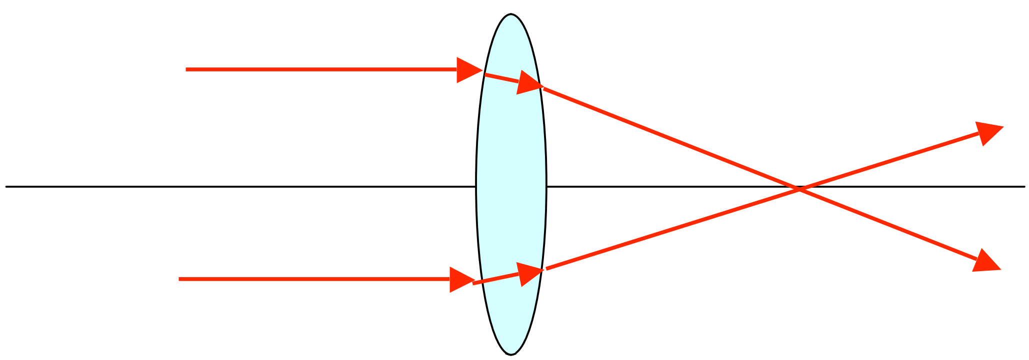


Figure 1 - A converging lens brings light rays to a focus

The law of refraction (Snell's law) tells us the direction that light bends when it goes from one material to another. Snell's law describes the angles that a ray of light makes as it enters and exits the surface between the two materials. These angles are measured from what is called a "normal line," that is, a line that makes a right angle (90°) to the surface. If light travels more slowly after it crosses the surface, it is bent toward the normal line. If it travels faster on the other side, it bends away from the normal line. This behavior explains how the lens is able to focus light to a point.

Figure 2 shows a beam of light from a laser entering a plate of glass and then leaving the glass on the other side. The laser light bends toward the normal line when it enters the glass and away from the normal line when it leaves the glass. This behavior of light explains how the glass lens works when it is used in air.

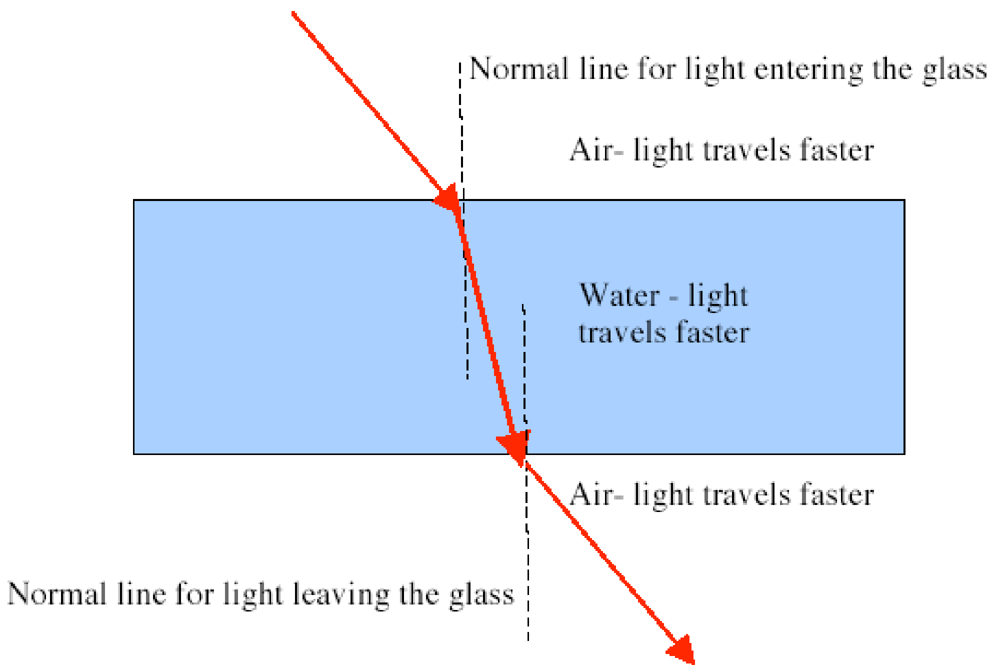


Figure 2 - Light bends toward the normal line when it enters a material where it travels more slowly (air to glass) and away from the normal line when it enters a material where it travels faster (glass to air)

Procedure:

1. First you need to make the "air lens". Clean the two watch glasses, then carefully squeeze a small bead of caulk all the way around the edge of one of them. Be sure there are no gaps, or your lens will leak! Gently push the second watch glass onto the first so that their edges are sealed together as shown in Figure 3. Let the caulk dry completely.

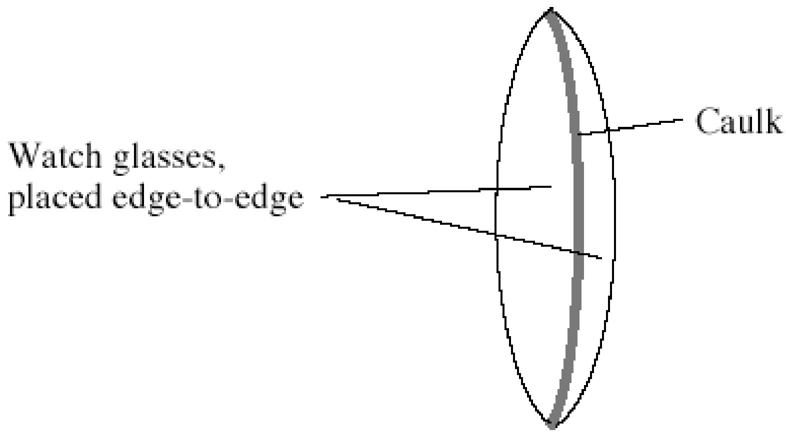


Figure 3 - Construction of the "air lens"

2. When the caulk is completely dry, fill the fish tank with water and submerge the lens. What do you think will happen when light goes through the air lens when it is under water? Use the flashlight focused to give a collimated beam. If you have a laser pointer, shine it into the lens along at several places and observe which way the light bends.

Observations:
Does the submerged air lens cause light to converge to a point or does it make the light spread out (diverge)?

Conclusion: What else besides the shape of a lens determines how it bends light passing through it? Sound travels faster in plastic than it does in air or water. What shape should a plastic lens have in order to focus an underwater beam of ultrasound?

8. Exploring Diffraction

CAUTION! Do not look into the laser cavity or at any reflections of the laser from shiny surfaces.

Question: How can you use a laser to measure the thickness of your hair?

Materials:

- Laser Pointer
- Tape measure or ruler
- 2 clothes pins

Background:

When light passes through a small opening or around a small object, the light appears to "bend" around the edges. Parts of the light wave then interfere with each other, creating patterns of dark and light. This is called diffraction.

You can see diffraction by holding two pencils close together side by side and looking at a light source through the tiny crack between them. A computer monitor works well as a light source, and you need to put your eye very close to the pencils. You will see dark and light bands - you may even see faint colors. The bands are caused by light waves bending around the edges of your fingers and interfering to cause dark and bright streaks. Note that the bands disappear if you spread your fingers apart. Diffraction is one of the most fascinating aspects of light!

In this exploration, you will tape a piece of hair across the output aperture of a laser. The laser light will diffract around the hair and a pattern of light and dark spots will form on a distant screen. We call the dark and bright spots "fringes". The spots are "named" according to their position relative to the center of the pattern. The bright spot in the center is called the "zero order fringe," and we indicate this mathematically by saying $m=0$. That is, m is the "order" of the fringe. The spots on either side of the center spot are the first order fringes ($m=1$), then the second order fringes ($m=2$) and so on.

Figure 1 shows how the fringes are numbered along the viewing screen. You will actually see many more fringes, and they will probably not be sharp lines as shown in the drawing. The center of the pattern will be a little blurry.

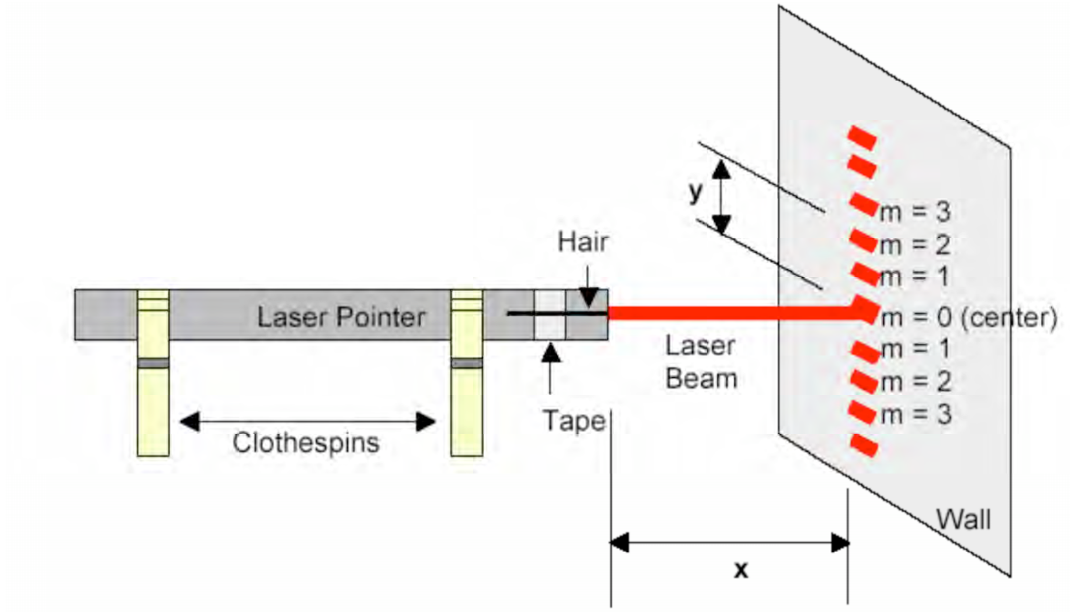


Figure 1 - Diffraction pattern caused by a hair. There are many more fringes than shown here, and they are much closer together than shown in this diagram. The distance "y" is shown to the *m*=2, or second order fringe.

By measuring the distance between the spots, you can calculate the diameter of the hair from the approximate formula

$$d = \frac{m\lambda x}{y}$$

In this formula:

d = diameter of the hair

m = the order of the fringe (1,2,3, etc.)

λ = the wavelength of the light (This is written on the laser warning label.)

x = the distance from the hair to the screen on the wall

y = the distance from center fringe (m = 0) to the ***m***th fringe.

You need to know which fringe (***m***) you are looking at, as well as the distance to the fringe.

Procedure:

1. Tape a piece of hair across the output aperture of a laser pointer. Support the laser pointer using two clothespins as shown in Figure 1.
2. Point the laser pointer at a wall (approximately 3 meters away, far enough so the fringes are separate enough to measure). Tape a piece of paper on the wall to serve as a screen.
3. Turn on the laser pointer and observe the pattern formed on the wall. With a pencil, mark the center of the pattern. Label this mark "***m***=0." Mark the positions of several fringes on either side and label their orders (***m***) as well.
4. Measure the distance from the laser pointer to the wall and record the value of ***x***. Take the paper down.
5. Measure the distance between the central fringe (***m***=0) and one of the other fringes. Also record ***m***, the order of the fringe whose distance you measured. Record the values of ***y*** and ***m***.
6. Record the wavelength of the laser. It should be listed on the side of the laser pointer (typically 650 nm or 670 nm). Be sure the laser is off when you look for the label!
7. Using the equation to calculate the diameter of the hair. It should be approximately 80-120 um.

Conclusions:

Compare your results with your classmates. Is there a difference between blonde and brown hair? Some students have measured the size of their pets' hair! What might be a practical use of this experiment?

Data for the Diffraction Experiment

Type of hair you used: ___________________________

x = _____________________

m = _____________________

y = _____________________

λ = _____________________

Calculated hair diameter: ________________________

9. Exploring Rayleigh's Criterion and Resolution

<u>Question:</u> How close together can dots be and still be seen as separate dots? Does it depend on the color of the dots?

Materials:

- Patterns of red dots and blue dots, 1 mm across, spaced 1 mm apart. Draw them on a piece of paper or print Figure 1 on white paper using a color printer.
- Meter stick

Background:

When light passes through a small opening, it spreads out, or diffracts. The diffraction pattern that results from light passing through a circular hole consists of a central bright disk (called the Airy disk) surrounded by dimmer rings of light around the disk in bulls eye fashion. The size of the center disk depends on the wavelength of the light, on the size of the hole and on how far the hole is from the viewing screen.

It might surprise you to learn that light passing through a small hole spreads more than light passing through a larger hole! Red light also spreads out more than blue light.

When light from two small points of light pass through the same hole, the light from each source will produce its own diffraction disk. Rayleigh's criterion states that you will be able to tell that there are two small dots rather than one dot (they are just resolved) when the center of one diffraction disk falls on the edge of the other. The pupil of your eye is a small round opening, so this result means that when light from two points, such as two stars, enters your eye you will be able to see them as two separate points if Rayleigh's criterion is satisfied. Rayleigh's criterion applies to the lenses of instruments such as microscopes and telescopes.

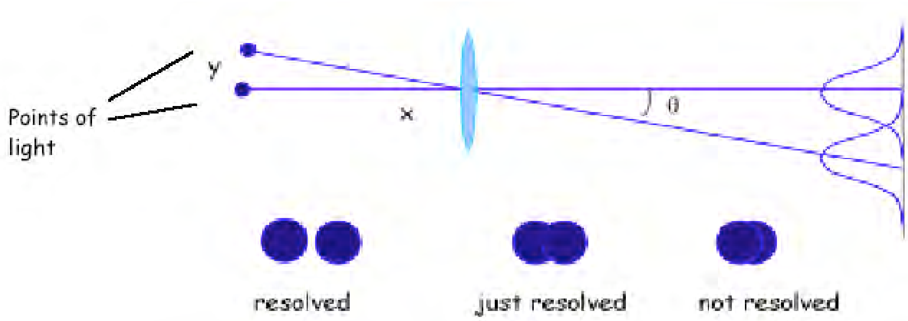


Figure 1 - Rayleigh's criterion

As you can see from Figure 1, the separation between the two diffraction disks depends on how far apart the points of light (***y***) are and how far away they are from the opening (***x***). The wavelength is also important.

Procedure:

1. Copy or print the pattern shown in Figure 2. Tape the pattern on a wall.
2. Stand far enough away from the patterns in a well-lighted room so that they appear to be solid lines. Walk slowly toward the patterns until each resolves into a set of dots.
3. Record the distance where you can see the separate blue dots and the distance where you can see the separate red dots.

Questions/Conclusions:

Does the distance at which the spots can be resolved depend on color (wavelength)? If so, how? Do your results agree with those of your classmates? Look at Figure 1 and explain why the result is not affected by the distance from the lens to the screen. Hint- What happens to the size of the disks and to the separation of the disks as this distance increases?

Further Exploration:

Diffraction and Rayleigh's criterion limits how small letters can be on highway signs and how close together lights on an airport tower can be. It also explains the style of painting called Pointillism, or stippling. In these paintings, millions of tiny dots merge together when viewed from a distance. In such paintings, two neighboring dots of different color can appear to form a third color when viewed from far away. How can this be? If you live near an art museum, see if they have any Pointillistic paintings on display and note at what distance the different color dots begin to merge.

What other common devices depend on colored dots appearing to merge together?

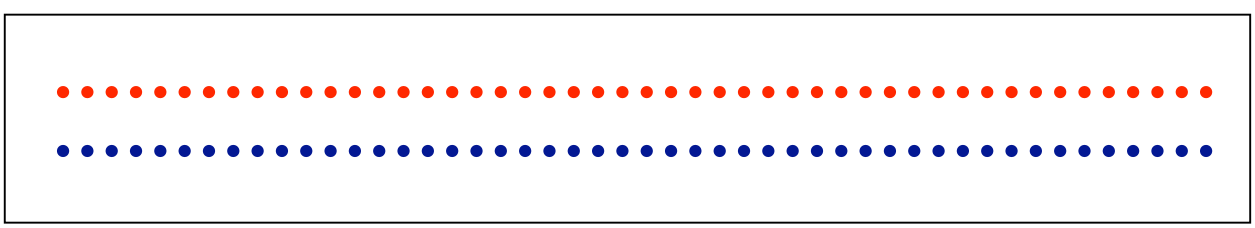


Figure 2 - Red and Blue dot pattern

10. Exploring Polarization

Question: **What is polarized light? How is polarized light produced?**

Materials:

- Two pieces of polarizing plastic from the OSA Optics Discovery kit. These are square, dark pieces of plastic covered by a thin plastic film. Remove the film to do the experiments.
- Bowl of water
- Transparent plastic objects: ruler, protractor, comb, etc.

Background:

As you know, light is a wave. The vibrations of light waves are perpendicular to the direction that the light is traveling. (See Figure 1.) "Natural" or randomly polarized light has light waves that vibrate in all directions, and the vibration directions vary randomly in time. In Figure 1, the top picture represents natural, unpolarized light. The wave is traveling toward the right, and two directions of vibration are shown, up and down and in and out of the page. Randomly polarized light allows vibration in many more directions but only two are shown in the drawing for simplicity.

The bottom diagram represents polarized light, with only up and down vibrations allowed. When light is polarized, the vibrations are in one direction only. Polarized light may be produced by passing it through a polarizing filter (sometimes called Polaroid® material), by scattering it from molecules, by reflecting it from a nonconductive surface, and by double refraction (passing light through a birefringent material, such as a calcite crystal).

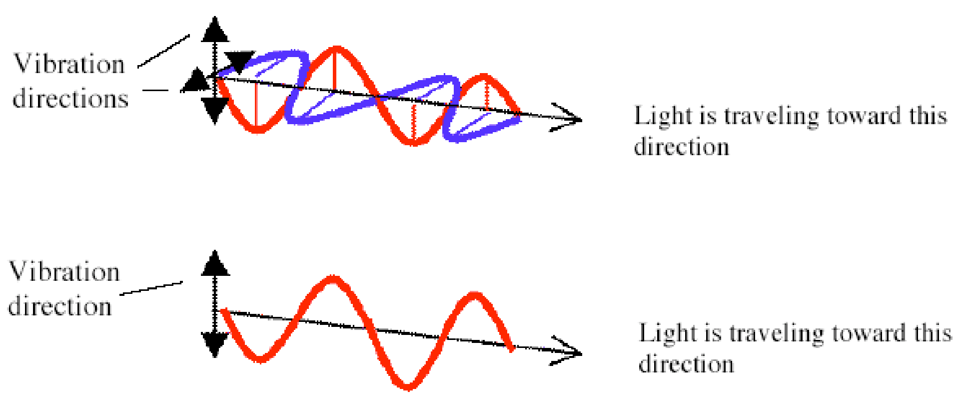


Figure 1 - Natural (top) and vertically polarized (bottom) light

Procedure:

1. Find the transmission axis of the polarizers (Polarization by reflection)

To determine the transmission axis of the polarizers, you need to view the glare or shine from a surface such as glass, water or ice. Place a bowl of water on a table or counter so that it reflects either the room lights or light from a window. Look at the reflection through one of the polarizing filters. Don't look directly down onto the surface, but view it from an angle as shown in Figure 2.

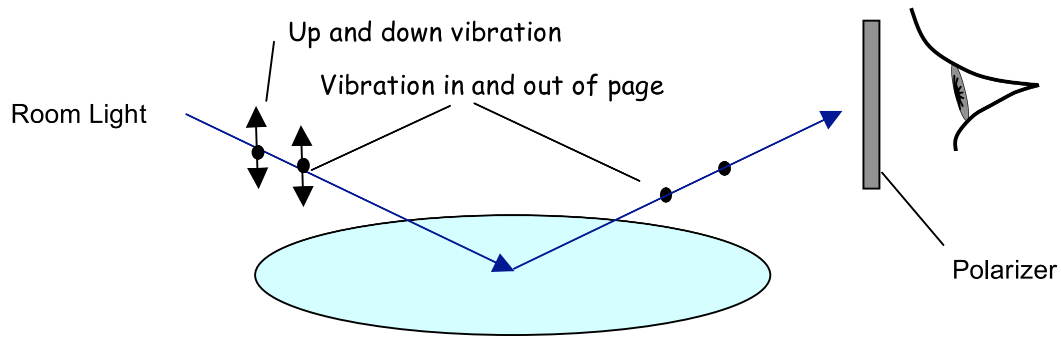


Figure 2 - Determining the transmission axis of the two polarizers. Randomly polarized light (on the left) is reflected so that it is polarized (on the right). The dots mean vibration in and out of the page (they represent the tail of an arrow).

While looking through the polarizer, rotate it and notice that the reflected light becomes dimmer and brighter. When you can see the reflection at its brightest, the transmission axis of the polarizer is horizontal. The waves reflected from the water are vibrating mostly horizontally and they can pass through the filter. The "dots" in Figure 2 indicate vibration in and out of the page. Like the slats in a fence, the polarizer is aligned to let this vibration through. Mark the polarizer with a piece of tape so you know which direction is the transmission axis. Repeat with the other polarizer.

2. Polarizer pair

Now that you have labeled the transmission axis of each polarizer, look through one of them at a source of light (a lamp is fine). The light you see passing through the polarizer is linearly polarized! You can change the direction of polarization by rotating the plastic. Your eye can't see the difference but if you were a honeybee you would notice!

Now hold the polarizer so that it is producing vertically polarized light. (The transmission axis is vertical.) Place the second polarizer in front of the first with its transmission axis also vertical. Without moving the first polarizer, rotate the second through 360 degrees (Figure 3).

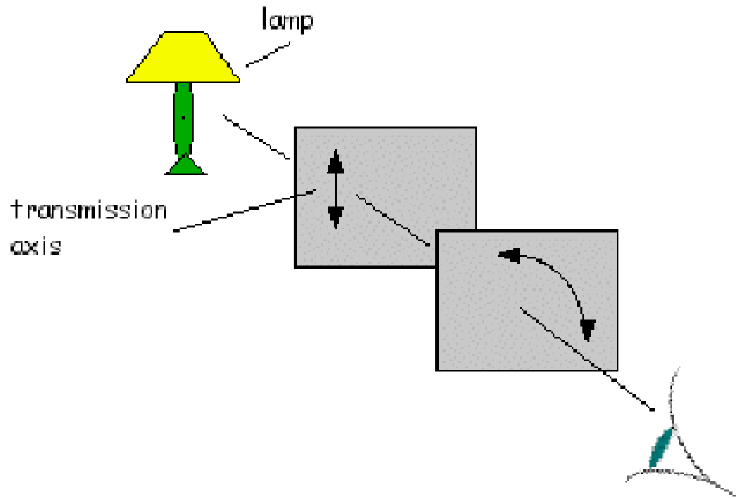


Figure 3 - Looking through two polarizers

Observation 1: How does the lamp appear when you look through one polarizer, compared to looking directly at it without a polarizer?

Observation 2: How many times does the light dim during the 360 degree rotation?

Conclusion: How does the polarization of light explain your observations?

3. Polarization by scattering

When light is scattered from molecules, the scattered light is polarized. This is called Rayleigh scattering. One molecular scatterer that is easy to find is air! On a sunny day, look at the blue sky through one of the polarizers. Look at a patch of sky AWAY from the sun, and rotate the polarizer in front of your eye as you look through it. Look at other parts of the sky as well. **DON'T LOOK AT THE SUN!**

Observation: What do you see when you rotate the polarizer?

Conclusion: What does this observation tell you about the light scattered by the atmosphere?

Bees and other insects use the polarization of the sky to navigate (their eyes are adapted to sense polarization). They have to stay home if the sky is cloudy!

4. Stress patterns in plastic (changing the direction of polarization)

Look through the two polarizers toward a lamp and turn them so the transmission axes are crossed and no light gets through. Look through the polarizers. Place a piece of plastic film (food wrap is fine) between the "crossed" polarizers, and stretch the plastic film. Look through both polarizers and the film.

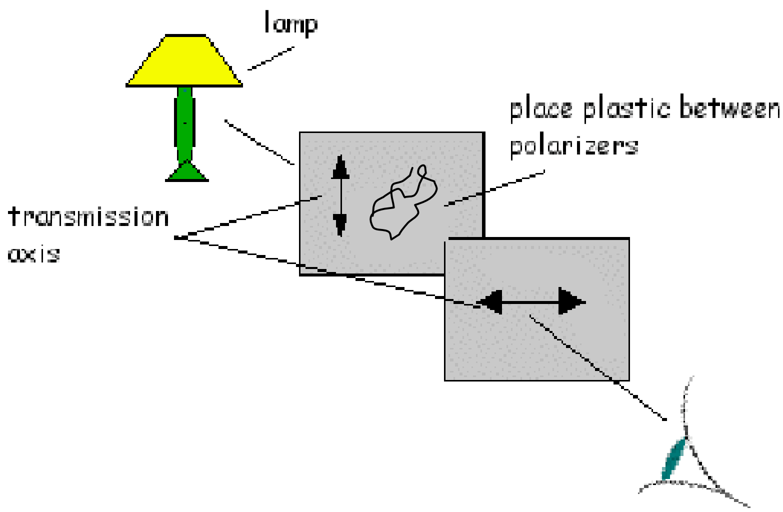


Figure 4 - Looking at stressed materials through polarizers

Observation 1: What do you see when you look through the crossed polarizers?

Observation 2: What effect does the film have?

Conclusion: What does the plastic film do to the polarized light passing through the first polarizer? What do you see when the plastic is stretched? The amount the plastic alters the polarization direction is wavelength (color) dependent.

Place other plastic transparent objects between the polarizers- a clear plastic ruler (twist it and see what happens), a comb, a protractor, or a pair of eyeglasses (look at the lenses). Any stresses in the material can be visualized in polarized light. If a model of a structure such as a bridge is built of transparent plastic, it can be weighted to simulate actual operating conditions. Viewing the model in polarized light helps to visualize where the structure will stressed.

11. The Magic Box - Exploring Polarization

<u>Question</u>: Can you use light to make a magic box with a "wall that isn't there"?

<u>Materials:</u>

- A small rectangular box such as a shoe box or tissue box
- Four 2"-3" square linear polarizing filters
- Tape
- For special effect- a long bladed knife (be careful!)

<u>Background:</u>

As you know, light is a wave and the vibrations of light waves are perpendicular to the direction that the light is traveling. "Natural" or randomly polarized light consists of light waves that vibrate in all directions, and the vibration directions vary randomly in time. When light is polarized, the vibrations are in one direction only.

In Figure 1, the light wave is moving toward the right in both the top and bottom diagrams. In the top diagram, two directions of vibration are shown, up and down and in and out of the page. Randomly polarized light allows vibration in many more directions but only two are shown for clarity. The bottom diagram represents polarized light with only up and down vibrations allowed.

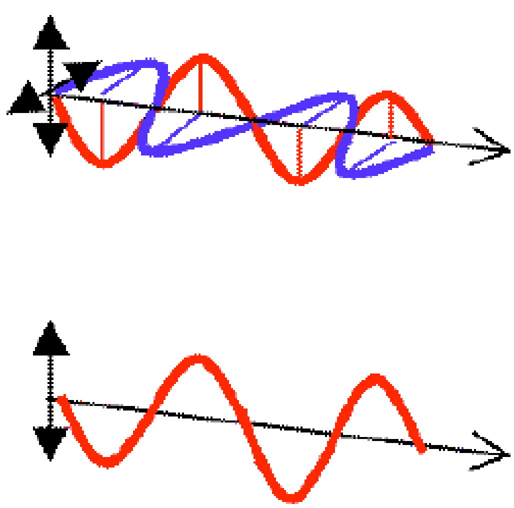


Figure 1 - Natural (top) and vertically polarized (bottom) light

Procedure:

1. To build the magic box, you need to remove rectangles approximately 2" by 4" from both the front and the back sides of the shoe box. Be sure that each opening can be completely covered by the two polarizer squares when they are placed side by side. Carefully align these openings so you can look right through the box.

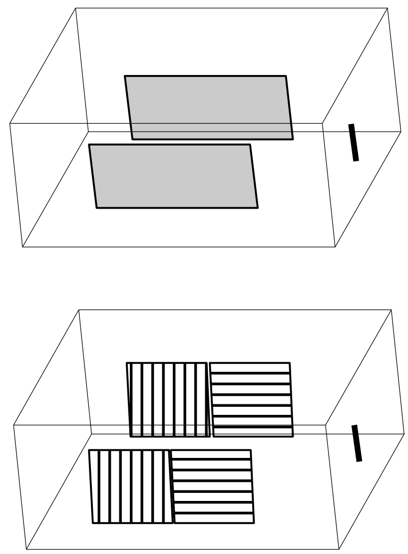


Figure 2. Construction of the magic box. top: Box with rectangles cut in the front and rear sides. middle: Front of box. Openings covered with polarizers. Direction of the transmission axis is indicated. bottom: Back of box. Direction of transmission axis is indicated.

2. Tape two of the polarizing filter squares to the front opening. One filter should have its transmission axis in the vertical direction and the other in the horizontal direction. Look through the box and describe what you see.

Observation 1: Do the polarizers look any different from each other?

3. Tape two of the polarizing filter squares over the back opening. The orientation of the transmission axes is correct if, when viewed from the front, the vertical polarizers (front and back) are both on the same side. (Figure 2)

Observation 2: What do you see when you look through the box now, when you look through both pairs of polarizers?

An amazing variation: Cut narrow slits on the opposite ends of the box. Run a knife through the box from one end to the other! (Be careful!) Note that the box looks neater if you tape the polarizers inside, but this is not necessary.

Conclusion: Where does the "wall" come from? How can the knife go through it?

Note for teachers:

To add a dramatic touch, do not tape the polarizers to the outside back of the box. Instead, attach them to the inside of the box making a tape "hinge" along the top side only. When the box is inverted, the filters will "flop" out of the way, inside the box, and students will look through only the front set of polarizers. The view through the box is slightly darkened, but otherwise unremarkable, since your eye is not sensitive to polarization direction. Flip the box over and the polarizers fall over the back opening, making the "magic wall" appear.

12. Polarized Light Art

Question: Can you use polarized light to make a colorful picture?

Materials:

- Two pieces of polarizing plastic from the OSA kit. These are square, dark pieces of plastic covered by a thin plastic film. Remove the protective film to do the experiments.
- Pieces of cellophane tape (clear packing tape works well) or you can use the cellophane wrapping material from produce such as lettuce or broccoli.
- A small square of clear plastic the same size as the polarizers such as a transparency master

Background:

Before you use polarized light to create art, you should do the polarized light exploration in this booklet. In *Exploring Polarized Light,* you learn that "natural" or randomly polarized light consists of light waves that vibrate in all directions, and the vibration direction varies randomly in time. When light is polarized, the vibrations are in one direction only. In this exploration, you will create polarized light by using a polarizing filter (Polaroid® material).

You also saw that if you placed two pieces of polarizing filter so the transmission axes are parallel, nearly all the light passes. If the transmission axes are at right angles, no light passes. But if you put certain types of material in between the crossed polarizers, some light may get through!

In this exploration we will use tape or cellophane to change the direction of polarization of light. You will make a "sandwich" with cellophane tape or plain cellophane between two pieces of polarizing film. Light will be polarized by the first polarizer, and then the direction of polarization is changed when it passes through the cellophane. The amount the polarization direction changes depends on the wavelength (color) of the light as well as the thickness and direction of the cellophane. If you then rotate the top polarizer, you will see different wavelengths at different angles of rotation.

Procedure:

1. Cut the pieces of cellophane or tape into various shapes. Experiment by varying the thickness of the shapes from one to several layers thick.
2. Stick the tape onto the plastic square. If you use plain cellophane you can attach it with a glue stick. The reason you should use a separate piece of plastic is to protect the polarizing film; it might be damaged if you attach the pieces to it directly.
3. When your piece of "art" is complete, place it on one of the polarizers and hold it up to a window or other light source. Put the other polarizer in front of the tape and rotate it, while looking through all three layers. (See Figure 1.)

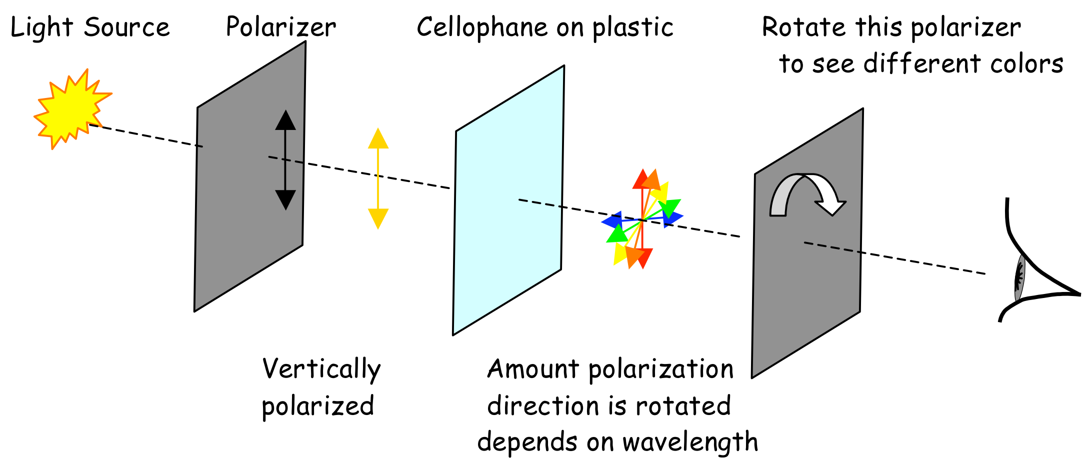


Figure 1 - Polarized Light Art

Conclusions:

Did the thickness and direction of the cellophane make a difference in the color you saw? What other materials would this work with besides cellophane?

More on polarized light art: Austine Woods Comorow is a well-known artist who uses this technique, which she calls ***Polage®***, to create beautiful works of art that change as you look at them through a moving polarizer. Some of her pieces cover complete walls in museums and other public spaces. You can see her art on her website http://www.austine.com.

For more on polarization in nature, visit http://www.polarization.com.

13. Exploring Scattering

Question: **Why is the sky blue?**

Materials:

- 1 fishtank (A small container will not work well.)
- 1 flashlight
- Several drops of milk or cream

Background:

The blue color of the sky is due mainly to a phenomenon called Rayleigh scattering. Rayleigh scattering occurs when light from the sun is scattered by the small particles that make up our atmosphere. If a beam of light contains many colors (wavelengths), the blue light in the beam will be scattered much more than the red light. That is, the scattering of light depends on its wavelength.

Sunlight contains all of the visible wavelengths. Rayleigh scattering will cause blue light to be scattered out of the sun's beam far more than the red light, which travels in a straighter path from sun to earth. This explains why the sky appears blue.

Rayleigh scattering may be observed in a fish tank filled with water to which a few drops of cream or milk have been added. This is illustrated in Figure 1. Compared to its color when viewed in air, a flashlight beam directed along the long axis of the tank will appear yellow when viewed from the end of the tank, and bluish when viewed from the side.

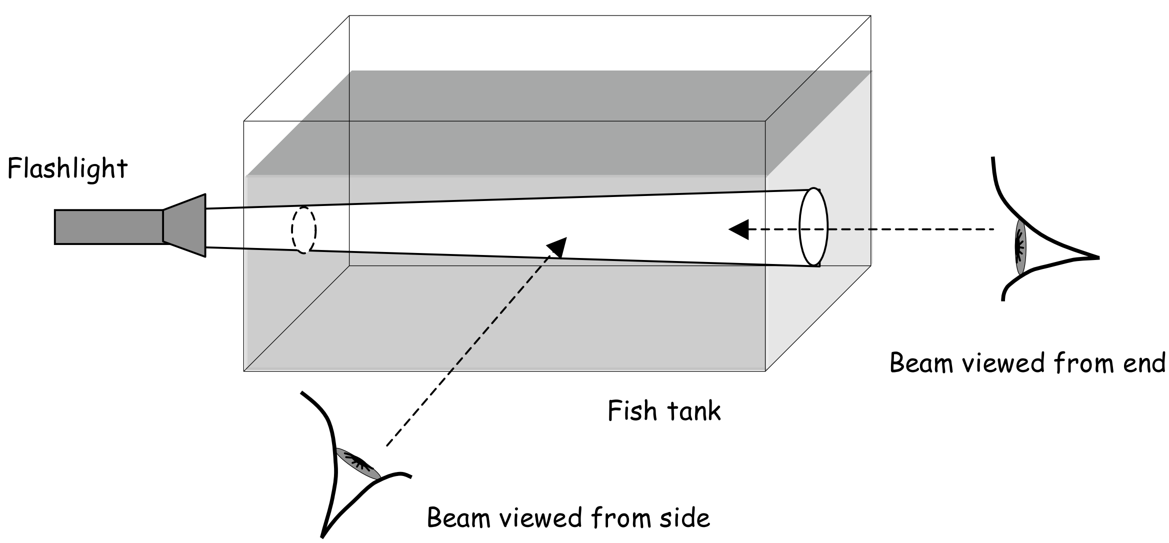


Figure 1 – Light scattered by liquid in a clear container

Procedure:

1. Fill the tank with water and add one or two drops of milk. Mix the water and milk in the tank so that it looks barely cloudy. Too much milk will ruin this experiment, so you need to add it one drop at a time and observe the results before adding more.
2. Shine the flashlight into one end of the tank as shown in Figure 1.
3. Observe the color of the flashlight beam in the tank from the side. What color is the beam tinted? The effect will be very slight.
4. Now view the beam from the end of the tank. What color is the beam now? Compare this to the color of the light when you look at it directly, not through the water.

Optional Exploration: Try this if you have already done the Polarization Exploration. Light that is scattered by Rayleigh scattering is also polarized. Take a piece of polarizing material and look at the beam through the side of the tank. Rotate the polarizing material in front of your eye (Figure 2). What do you see? Look into the end of the tank, toward the light, and repeat. Is the light coming directly toward you polarized also? Some insects have special structures in their eyes that can detect polarization. How might being able to see polarized light help them navigate?

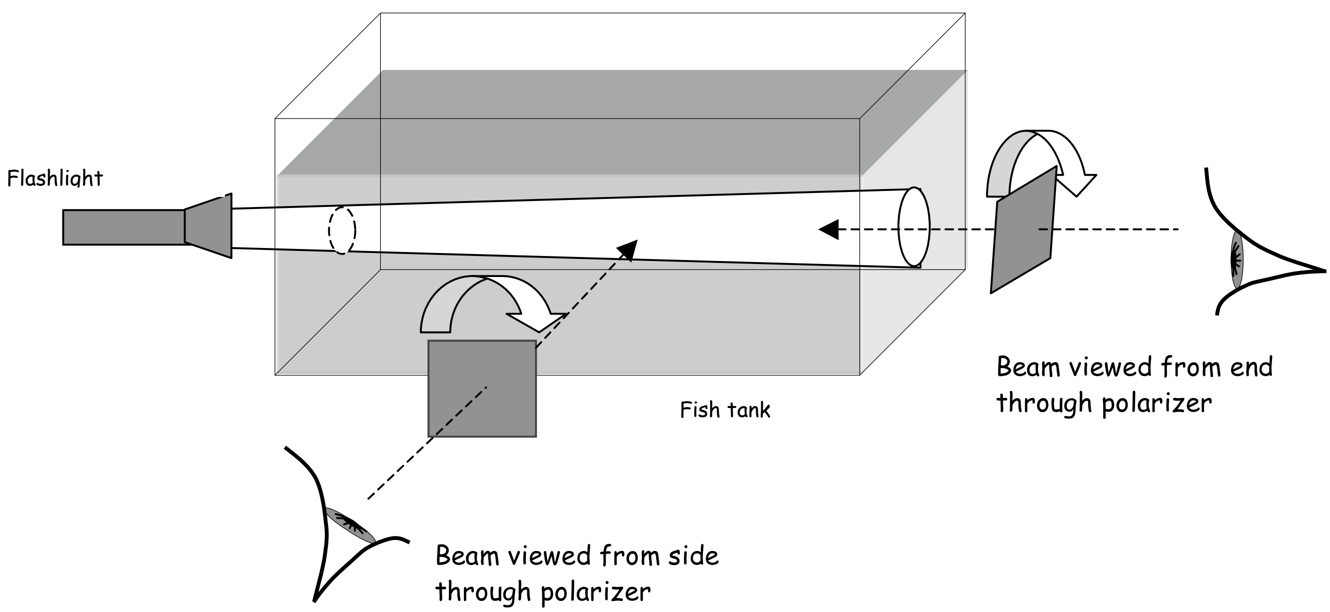


Figure 2 - Polarization of Rayleigh Scattered Light

Conclusion:

Which end of the light spectrum, blue or red, is scattered out of the beam toward the sides of the tank? Which end of the spectrum, blue or red, is not scattered as much and goes from one end of the tank to the other? In your own words, use the results of this experiment to explain why the sky is blue and why the sun appears red at sunset.

14. Exploring Laser Beams

CAUTION! Do not look into the laser cavity or at any reflections of the laser from shiny surfaces.

Question: **Does laser light spread out as the beam travels through space? How else is a laser beam different from a flashlight?**

Materials:

- Laser pointer
- Flashlight
- A CD or DVD
- Piece of waxed paper or frosted glass
- Meter stick and ruler

Background:

The term LASER is an acronym. It stands for **L**ight **A**mplification through the **S**timulated **E**mission of **R**adiation. A laser is a special type of light source that has unique properties that make it very important for today's technologies. Unlike a flashlight, a laser typically produces one wavelength (or color). Laser light is extremely bright. Lasers can be brighter than the sun! Laser light also spreads out very little when shined across a distance. (See Figure 1.)

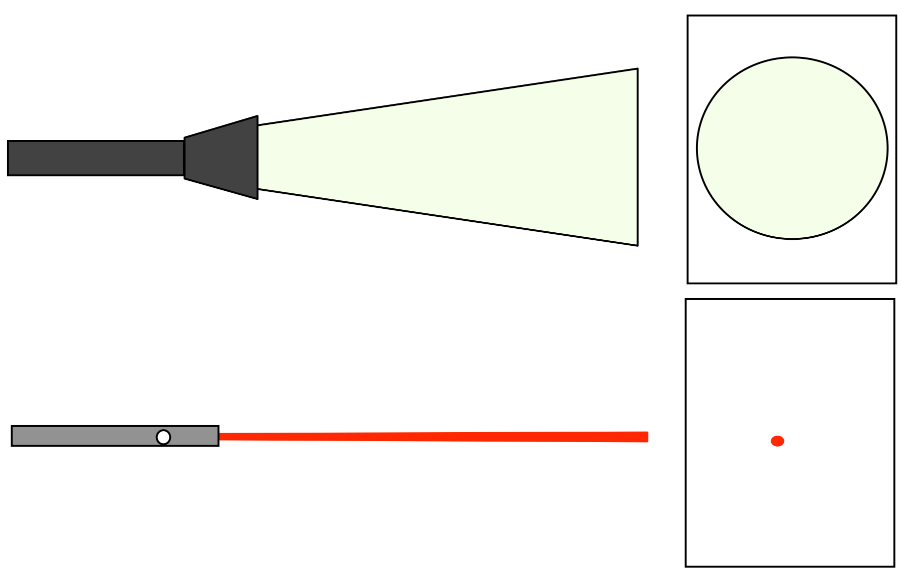


Figure 1 – Flash Light vs. Laser Pointer. Flashlights produce "white" light, while lasers pointers produce colored light. The spots of light produced by each type of light may be seen by shining it on a piece of paper taped to a wall.

The special properties allow laser beams to:

- Travel very far distances (to the moon and back!)
- Be focused down to very small spots (to less than 1/10 the size of a human hair) for cutting, welding, and drilling steel and other really hard materials
- Make very precise measurements (like measuring the size of an atom)
- Cut tissue in laser surgery without blood

You know that when you turn on the light bulb in a lamp in your home, the light spreads to illuminate the entire room. A flashlight beam, on the other hand, spreads less and illuminates a only circular area. We call this spreading of a light *divergence*. Do you think a laser beam spreads out? After all, laser pointers are used to make small spots on a screen across the room!

In this exploration, you will find out if a laser beam diverges and learn some other ways a laser is different from a flashlight.

Procedure:

1. Tape a piece of white paper on the wall.
2. Working with a partner, hold the flashlight about one half meter from the wall and shine it onto the piece of paper. Mark the "edges" (diameter) of the beam. You will have to make your best guess about where the beam edges are. Repeat with the laser.
3. Move back as far as you can from the wall and shine the flashlight onto the piece of paper again. Again, mark the diameter of the beam. Repeat with the laser. BE CAREFUL not to shine the laser in anyone's eye! Keep the beam well below eye level.

Observation 1: Which beam spreads more, the flashlight or the laser? Why do you think so?

4. Now take the laser and carefully reflect the beam from the CD or DVD onto the paper on the wall. Record your observation.
5. Repeat step 4 with the laser. Be very careful not to reflect the beam into anyone's eyes! Record your observation.

OBSERVATION 2: What colors make up the flashlight beam? What about the laser beam?

QUESTION: What does *monochromatic* mean?

6. Put the waxed paper over the end of the flashlight and shine it on the paper. (Or, pass the flashlight beam through a piece of frosted glass.) What do you see on the paper?
7. Repeat step 6 with the laser. Does the laser light look different (aside from being red)?

OBSERVATION 3: Describe how laser *speckle* is different from ordinary light.

OPTIONAL- Using math to predict the size of a laser beam
You will need to carefully measure the diameter of the beam at two different distances from the lasers. You also need to measure the distance between the wall and the laser each time.

8. As in part 2, hold the laser about one half meter from the wall so the beam is on the piece of paper. With your tape measure, measure the actual distance from the wall and record this distance as $\mathbf{X_1}$. See Figure 2.
9. Measure the diameter of the beam. One way to do this is to mark what seem to be the edges of the beam on the paper with a pencil, then turn off the laser and measure the distance between the marks. Record this value as $\mathbf{D_1}$.
10. Move back as far as you can from the wall and shine the laser onto the piece of paper again. BE CAREFUL not to shine the laser in anyone's eye! Keep the beam well below eye level.
11. With your tape measure, measure the diameter of the beam again. Record this value as $\mathbf{D_2}$.
12. With your tape measure, measure the distance from the wall. Record this value as $\mathbf{X_2}$.

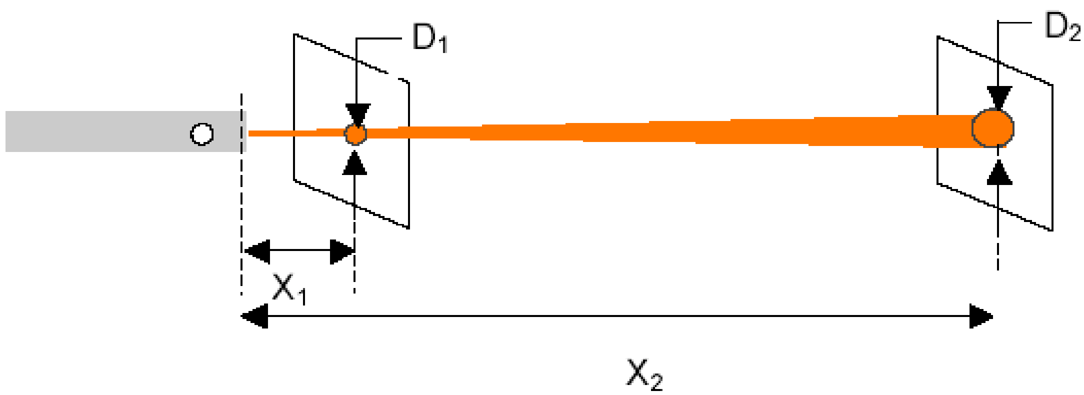


Figure 2 - Measurements to determine spreading of laser beam

DATA from Steps 9-13

X_1=____________ D_1=_______________

X_2=____________ D_2=_______________

13. Using the following formula, calculate how large the beam will be at a distance X_3 when X_3 is:
    a. 100 meters away
    b. 1609 meters away (1 mile)
    c. 385,000,000 meters away (239,000 miles away, the average distance to the moon)

$$\text{Beam Diameter at } X_3 = \frac{D_2 - D_1}{X_2 - X_1} \cdot X_3$$

CONCLUSION:

How is a laser beam different from a flashlight? Name as many differences as you can.

Does a laser beam spread out as it travels through space? How big will the laser beam be on the moon? Why can't you shine a flashlight on the moon and have the reflection be received back on Earth?

15. Exploring Fluorescence and Phosphorescence

CAUTION! Do not stare at the UV light or shine it in someone's face.

Question: **How does fluorescence differ from phosphorescence?**

Materials:

- UV light
- Other light sources such as a red laser pointer and colored LED lights
- A square of glow-in-the-dark material (or glow-in-the-dark stars)
- Fluorescent minerals or other fluorescent materials such as whitening detergent, UV ink

Background:

Visible light is produced when atoms in a high energy ("excited") level return to a lower energy level. Atoms can be excited in a number of ways, for example, when an atom absorbs light or is subjected to a high voltage. The excited atoms in a material may all give off their energy quickly, called fluorescence. Or the various atoms may release energy over a longer period of time causing phosphorescence.

The ultraviolet light waves used in this exploration has a high frequency and high energy. By comparison, red light has a low frequency and low energy. The energy of light is proportional to frequency, so if you can put the colors of the rainbow in order by increasing frequency, you also know their order by increasing energy!

Procedure - Phosphorescence:

1. In a darkened room (it does not need to be completely dark), place the square of glow-in-the-dark material or glow-in-the-dark stars on a table. Predict what will happen if you shine each of the lights- visible and ultraviolet- onto the material.
2. Test your predictions by shining each of the lights onto the material. Record which colored lights (including UV) make the material glow. How long does the material glow after the light is removed? How can you make the glow last longer after the light is removed? Were there any surprises?

Procedure - Fluorescence:

1. Observe the fluorescent materials under normal room lights.
2. Now turn off the room lights so that the room is quite dark. If you cannot darken the room sufficiently, put the materials inside a deep box to shade them from as much light as possible. Shine the UV light on the materials and observe and record any differences in appearances when the light is on compared to when it is off. Does the glow last after the light is removed?
3. Try the other colored lights- do you notice anything?

Conclusion:

Both fluorescence and phosphorescence result from atoms releasing energy in the form of light. What is the difference between them? Is the light produced by fluorescence and phosphorescence higher or lower energy than the light that you shine on the material to produce the effect? How do you know?

16. Exploring UV Light and Sunscreen Lotion

CAUTION! Do not stare at the UV light or shine it in someone's face.

Question: **How well does sunscreen protect against UV light?**

Materials:

- UV light (or you can use the sun- do not look at the sun!)
- UV beads
- Different types of sunscreen lotion
- Small pieces of glass or plastic wrap
- Brown plastic medicine container

Background:

UV beads contain a pigment that responds to ultraviolet light by changing color. UV light is high energy and can cause damage such as sunburn, wrinkled skin and skin cancer. Sunscreen lotions protect against UV by absorbing the light so it does not reach the skin.

Procedure- Phosphorescence:

1. Expose the UV beads to the ultraviolet light or to the sun. What do you observe?
2. Place the beads under the glass or plastic- do they still change color?
3. Spread the sunscreen on the glass or plastic wrap. (You could put it directly on the beads but it's messy!) Place it over the beads and expose to the UV light again. What do you observe? Is all of the UV light blocked? If you have different types of sunscreen lotion compare the effects of different types.
4. Place the beads in the medicine container and expose to UV light. Do the beads change color?

Conclusion:

How does sunscreen protect your skin from ultraviolet light? Are all sunscreen lotions equally effective? Why might you want to protect medicine from ultraviolet light?