Optics Magic

Easy Demonstrations from the PHOTON Projects

Make glass disappear! Turn a tomato into a plum! See a "solid" wall vanish before your eyes and more. It's all done with optics

A project of the **PHOTON Projects** and the **PBL Projects** funded by the National Science Foundation/Advanced Technological Education program

www.pblprojects.org

April, 2020

The PHOTON Projects (FOTEP, DUE # 9553762 ; PHOTON, DUE # 0053284, PHOTON2 DUE # 0302528) and the PBL Projects (Advanced Photonics Manufacturing PBL, DUE # 1801115 ; Advanced Manufacturing PBL , DUE #1204941; STEM PBL , DUE #0903051 ; PHOTON PBL, DUE # 0603143) were funded by the National Science Foundation's Advanced Technological Education program (NSF ATE). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

Where the activities come from…

The PHOTON Projects of the New England Board of Higher Education were funded by the National Science Foundation's Advanced Technology Education program to develop curricula and materials for teaching optics/photonics and provide professional development in their use for secondary and post-secondary instructors. The *Explorations in Optics (2010)* were adapted from some of the favorite demonstrations of the projects' participants. We have used them with students from 5th grade through high school in outreach programs, and with the addition of calculations as part of a distance-learning course for working technicians and teacher professional development

In many of the following demonstrations and experiments, there is an element of "optical magic" to be investigated. When doing these activities with students, we begin by posing one or more questions while demonstrating the "magic trick." Students are then challenged to explain what they have seen based on their knowledge of light and optics. Finally, we provide practical applications of the principles involved to show that optics is more than magic, it affects students' daily lives.

Most of these demonstrations and activities use inexpensive and commonly found materials. They have all been student and teacher tested, but it's always a good idea to try them out first. Before doing any optics activities, be sure to find out in advance what the room lighting is like. Usually just turning room lights off is enough, but sometimes you might need to improvise if an activity works best in darkness.

The sixteen original *Explorations in Optics* are available at www.pblprojects.org in the Photonics Teaching Resources section. On the same website you can find links to short video demonstrations as well as two dozen grainy videos of ourselves doing the more advanced PHOTON Projects experiments. Full-hour lessons based on these demonstrations are available as *Dumpster Optics* on the same site. These lessons are in both English and Spanish and include both PowerPoint slides and teachers' notes.

A note on yhr "how it works" sections: The explanations here are aimed at 10-12 year olds, that is, 4th-6th graders in the U.S. Of course you can adjust them to the sophistication of your audience, but if you can explain physics to a ten-year-old you can explain it to anyone.

At the end of these instructions we provide additional information on materials as well as sources for the more "scientific" materials if you prefer to use them. Certain activities require inexpensive but not necessarily household items (like a chemistry lab watch glass). These are indicated in the instructions and sources for finding them are in the notes at the end.

Tomatoes and Rainbows – Magic with Color

#1 What color is a tomato?

Video: [***https://youtu.be/o7K_PYqylQY***](https://youtu.be/o7K_PYqylQY)

Can your eyes be fooled by color and lighting? What determines the color you see when you look at an object?

This is an easy demonstration. It's amazing how many kids think that a tomato appears red because it absorbs red light. Perhaps this will convince them otherwise.

Materials:

- A small tomato, plum or tangerine work well. You can also use small colored candies and challenge students to correctly identify the color to win the candy.
- At least two different color lights like finger LEDs or Christmas tree lights. You could also use a flashlight, covering the end with blue, green or red plastic film or a tightly stretched balloon.

Procedure:

In a very dark room, hold the tomato in your hand so that only a small portion of the surface is visible. If you are unable to darken the room, place the tomato or a few pieces of colorful candy in a small box so that it is well shaded from ambient light. It helps to paint the inside of the box flat black to minimize reflections. Illuminate the tomato or candy with one of the LEDs (the colored light) and observe the color of the illuminated surface. For example, a red tomato under blue light looks like a purple plum.

How it works

The color you see depends on the wavelengths reflected by the object, the wavelengths present in the illumination, and the color sensitivity of your eyes. A red tomato reflects a range of wavelengths, primarily red but also extending into the orange.[1] However, the skin is shiny so when it's illuminated by a blue LED, blue light is reflected but no red light since the LED does not contain red light. If there is some stray (white) light in the room, then the red content of that light is also reflected- and the tomato looks like a purple plum!

Application

Lighting plays an important role in marketing. The photo below shows the effect of illumination on a retail store display. Even though the items are identical on both left and right sides of the photo, the difference in lighting creates a large difference in perceived color. Check out the lighting in a local supermarket–are the same lights used for meat and produce? In my hometown, there was a notorious warehouse store where you had to check every item near the windows to see the "real" color. (It's now out of business.) The lighting departments of many hardware stores have displays of different bulbs illuminating the same colors, showing how lighting affects perceived color.

Figure 1. Photo taken at the Southern California Edison Lighting Center, 2004. The displays are the same colors on both sides of the wall, only the lighting is different.

#2 Colors of Light

Video: https://youtu.be/pRbpLYPrMbA

Is a red light bulb really red? Are some red lights more "red" than others?

OK, so this isn't so much magical (although kids find it really interesting) but it's easy and very inexpensive to do with a big group. Don't forget to mention safety! Many kids apparently don't know you shouldn't look at the sun.

Materials:

- Cardboard tube – a paper towel tube (cut to 15 cm) or toilet tissue tube.
- Plastic transmission diffraction grating. You can buy them or make one by peeling the label from an old recordable CD with a piece of tape (scratch the label first then pull off the label with tape). Use sturdy scissors to cut the CD into a piece that fits the end of the tube.
- Aluminum foil
- "CAUTION: DO NOT LOOK AT THE SUN OR INTO A LASER" sticker!

Procedure:

- Cover one end of a cardboard tube with aluminum foil. Hold the foil in place with a rubber band.

- Poke a small hole (about 2-3 mm) in the center of the foil with the point of a pencil or, if you can do it neatly, cut a small slit with a sharp knife.
- Place the diffraction grating or CD piece on the other end of the tube. Usually we don't glue the grating so it can be used without the tube for other experiments. It's fine to glue the CD when it's in the right position. The spectrum should be spread out from side to side (especially important if you used a slit rather than a small hole).

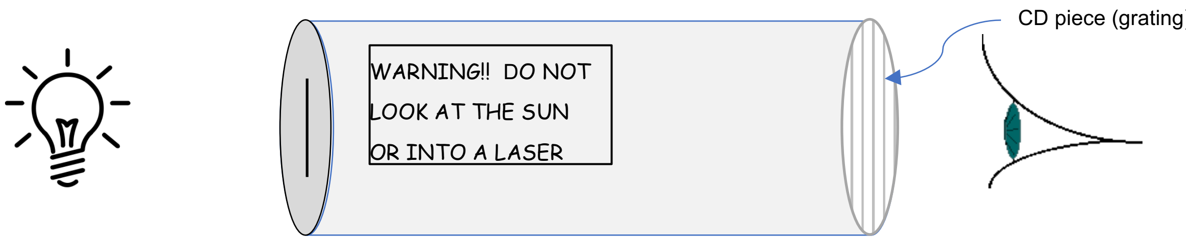


Figure 2. The cardboard tube spectroscope. Look into the CD piece on the back end of the tube. This shows a slit on the front end but you can also just poke a small hole.

- Don't forget the safety sticker!
- To use, look through the grating at a light source. Good sources are incandescent and CFL bulbs, ceiling lights, EXIT signs, etc. If you want to look at a laser's spectrum, use a laser pointer and shine the light onto a piece of white paper. Look at the reflection.

Figure 3. The grating or piece of CD needs to be rotated until the spectrum extends on either side (horizontally). This is what it looks like looking into the tube when a slit is used and everything is oriented properly. If you poked a hole rather than a slit there will be a bright dot in the center and streaks to the left and right. (Shown using an incandescent lamp.)

How it works

Whether a continuous spectrum for an incandescent bulb or "patches of color" (to quote a fifth grader) for compact fluorescent, different spectra reflect that each source creates light in a different way. Students are encouraged to bring their "spectroscopes" home and look at light sources around the house- BUT DO NOT LOOK AT THE SUN. (As with a laser, you can view the solar spectrum by looking at the reflection of sunlight from a piece of white paper.) Neon lights, exit signs and LED indicator lights are also interesting to look at. You can provide crayons or colored pencils so the students can draw what they see, which may be easier than a written description. Students may ask why we don't use a prism- they're expensive!

Application

There are lots of spectroscopy applications that appeal to young students. One we like is using spectra reflected from crops to tell if they are healthy or sick. (for example, phys.org/news/2017-04-drones-early-disease-crops.html) But we like to finish this activity by talking about how your eyes can be fooled. We show students a red "party light" bulb and ask them to predict what the spectrum looks like. (This is an incandescent bulb with a red coating.) Nearly every fifth grader will say red, "maybe with a little orange." In fact, the spectrum will appear nearly the same as the white incandescent they saw earlier, with plenty of green and some blue. Comparing this spectrum to that of a red LED leads to a discussion of how light is generated by different sources. Another interesting comparison is between "old fashioned" incandescent Christmas tree lights (if you can find them) and the newer LED light strings.

Magical Light Rays

#3 Pinhole Viewer

Video: *https://youtu.be/iF4qq39NsGY*

Can you make an image with just a cardboard box and a pinhole?

We like to do pinhole photography with older kids, making the cameras out of oatmeal boxes. (For example, users.rcn.com/stewoody/makecam.htm) But it's messy, needs a darkroom and produces potentially hazardous (silver bearing) waste. Here's an easy no-mess version to illustrate the same principle.

Materials

- Large carton or box (35-40 cm on a side is about right)
- Aluminum foil
- Sewing needle
- Electrical tape as needed to cover holes
- Waxed paper

Procedure:

- Cut a hole 1- 2 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. (Cover the ends and corners with black electrical tape, if necessary.)
- 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 sewing needle. The inner foil pieces should have neat pinholes, 1-2 mm wide with clean edges. Tape one of these foil pieces over the hole in the box, centering the pinhole on the larger hole.
- Cut a viewing hole about 10-15 cm square on the back of the carton. Cover the hole with waxed paper and to use as a screen. In a darkened room, aim the pinhole toward an open window (on a bright day) or a nearby lamp. An image will form on the waxed paper at the back of the box. ALTERNATE METHOD: Instead of a wax paper screen, use the inside of the box to see the image. To do this, leave the bottom of the box open, do not cut a hole in the back and hold the carton over your head. Look for the image on the inside of the box facing the pinhole. This works best with a bright light bulb as the object.
- What does the image look like? Is it right side up or upside down? What happens if you make the pinhole larger? Is there an optimum size? Why do pinhole photos have such long exposure times?

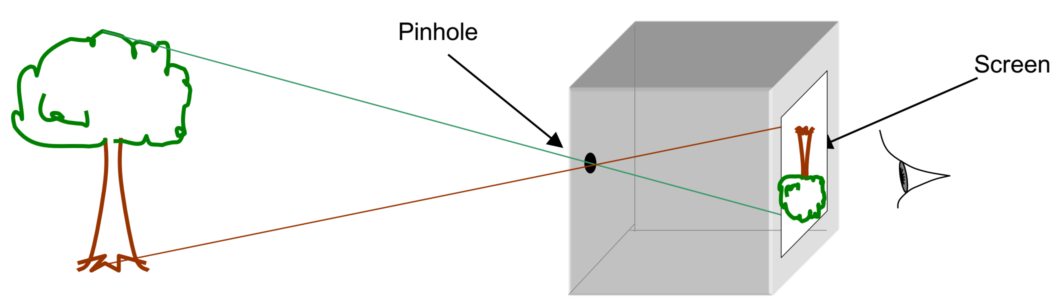


Figure 4. Using the pinhole viewer

How it works

As you can see in Figure 4, rays of sunlight reflected from the top of the tree pass through the pinhole and strike a small area on the end of the box. The rays from the bottom of the tree do not overlap the rays from the top because of the small size of the pinhole. Thus, an image of the tree is formed on the back of the box. The image is upside down and its size can be found by geometry (similar triangles).

If the hole is too large, the overlapping rays will form a blurry image, or no image at all. If it's too small, the image will be very dim. To use the box as a camera, it must have no light leaks and the film is placed on the inside, at the image location. Exposure times can be very long – several second outside on a sunny day to up to several hours indoors.

Note: A *Dumpster Optics* lesson exploring light rays and the formation of pinhole images can be found at www.pblprojects.org.

Applications

Many photographers enjoy creating pinhole images because of their unusual qualities. Cameras with laser drilled pinholes can be bought online, or cardboard cartons and oatmeal containers can be used to make simple "recycled junk cameras" to be used with film paper for quickly developed black and white photos. There are many web references for beginner to accomplished pinhole photographer; a few are listed in the resources at the end of these notes.

A very common (but often unrecognized) pinhole image can be seen under the canopies of leafy trees. The round blotches on the ground are pinhole images of the sun; these round spots turn to crescents during a solar eclipse.

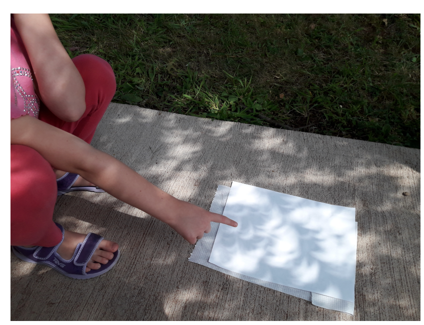


Figure 5. (Left) Oatmeal box cameras are curved, resulting in strange curved photos (Center) Pinhole images of the sun under dense vines (Right) Pinhole images of the sun under a tree during a partial eclipse of the sun.

#4 The Amazing Bedazzled Kaleidoscope

This experiment requires three large wall mirrors

How many times can you multiply yourself?

This is a wonderful activity and is actually less expensive than making kaleidoscopes with kits for a whole classroom. Using plastic mirrors makes the it more portable but also quite a bit more expensive.

Materials

- Three large mirrors (we use the kind you mount on the back of a door or a wall, available inexpensively at big box stores).
- Duct tape, lots of it
- Optional: Decorations for the backs of the mirrors

Procedure:

- Carefully tape the three mirrors together at their edges. Tape around the edges of the two openings as well. The mirror part should be facing inward.
- Optional: Decorate the outside (backs) of the mirrors with jewels, stick-on sparkles, etc. This really grabs attention.
- To use: Have students stand on each end and look into the kaleidoscope opening. Ask: How many faces do you see? Are they complete faces or parts of faces?
- Try looking at other objects such as a large number “5” (look at the orientation of reflections), or bright colored pictures.

How it works

Kaleidoscopes work by reflection, but the explanation for the formation of multiple images is not a simple exercise, especially for the 10-12-year-old audience. Two small mirrors can be used to illustrate multiple reflections after students have their curiosity piqued by using the giant kaleidoscope. (See the *Dumpster Optics* lesson on reflection available at www.pblprojects.org. It uses CD jewel cases for mirrors.)

Place the mirrors so they stand vertically making an angle of around 120^{o}. (It helps to have a “hinge” of tape to hold the mirrors together.) Place a small object such as a cork between the mirrors. As shown in Figure 6, an image forms in each of the mirrors, as expected. As the angle between the mirrors is made smaller more images appear due to multiple reflections. An interesting exercise is to count the number of images that appear as the angle between the mirrors is made smaller. Using a printed number “5” for the object lets students observe the orientation of the multiple reflections.

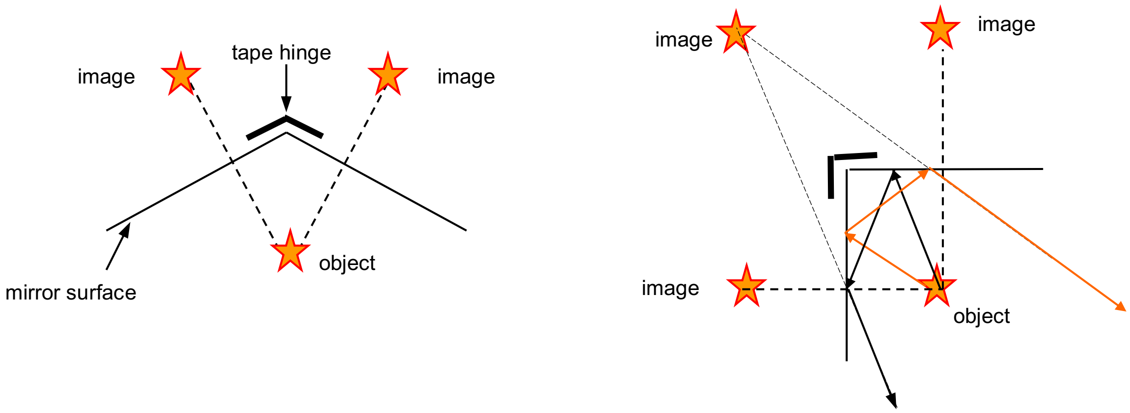


Figure 6. Images formed by two hinged mirrors at 120° (left) and 90° (right).

Application

Of course, the first example students usually think of is the mirror in a dressing room. But kaleidoscopes are interesting in their own right. Since its invention by Sir David Brewster in 1816, the kaleidoscope has been enthusiastically embraced by both curious children and serious artists. The Brewster Kaleidoscope Society (www.brewstersociety.com/) was founded in 1986 “to share and promote the beauty, creativity, and joy of these mirrored tubes of magic.” The society’s web site has links to kaleidoscope artists in the U.S., U.K. and Japan as well as diagrams showing how the number and orientation of images change as the angle between the mirrors change.

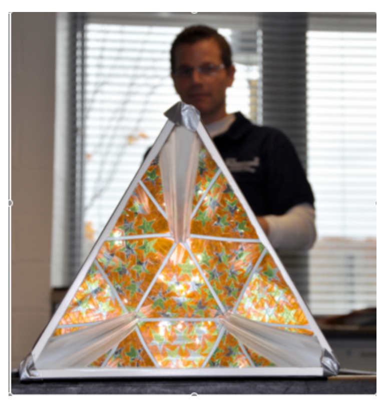


Figure 7. Using the Giant Bedazzled Kaleidoscope with 5th graders. Left: looking at and photographing faces Right: with colorful stickers on a clear plastic sheet as the object.

#5 The Disappearing Beaker

This experiment was written for beakers, but any nesting Pyrex® cups will do.

Video: https://youtu.be/86Hv5-4qlt0

Can a solid glass beaker disappear before your eyes?

This is a classic demonstration and you can find lots of video presentations on the web. Start by asking what "transparent" means. Students usually reply that it means you can see *through* something. So then how can you see something that's transparent, like a drinking glass? (The *Dumpster Optics* lesson on reflection addresses the importance of reflection to seeing.)

Materials:

- Two Pyrex® beakers or custard cups, a small one that fits completely inside the larger one. Other types of glass may or may not work – experiment to find out! The inner glass is the one that's important- a small Pyrex® cup inside a different glass container would work.
- Inexpensive vegetable oil (really- don't use that expensive olive oil here)

Procedure:

- Begin by placing the small beaker or cup inside the larger one, and noting that the inner beaker is plainly visible. (Why, if glass is "transparent"?)
- Pour some oil into the smaller beaker. Is it still visible? Why?
- Continue to pour oil in the smaller beaker until it overflows into the larger beaker. As the space between the two beakers fills with oil, the inside beaker disappears!

There are a lot of variations on this demonstration. One teacher started with the smaller beaker already submerged in oil. He then broke a beaker and dropped the pieces into the submerged beaker. After some magic words, he pulled out the inner beaker in one piece! The broken pieces can't be seen because they are submerged in the oil.

This demonstration may also be done with water (and far less mess) using gel beads from craft stores. (Look in the flower arranging aisle.) When saturated, they are nearly all water so they can't be seen when submerged in water. It does take a while for them to fully expand, however. If you want to dry the beads use distilled water or they will turn brown as they dry. Try offering the glass of "invisible" beads to a student and asking them to put their hand in to feel what's inside.

The Disappearing Beaker: How it works

In order to see an object, some light must leave the object and enter your eye. In the case of a non-luminous object, light must be reflected from the object in order for you to see it. That is, a transparent beaker must reflect at least a small amount of light in order for you to see it. For young students, the explanation is that when light slows down or speeds up, some light is reflected. Light slows down when it goes from air into glass, then speeds up when it leaves. But light travels at about the same speed in glass and in vegetable oil, so there is no reflection.

Older students who know about index of refraction (*n,* a measure of the speed of light) can calculate how much light is reflected. When light strikes glass head-on, the percent of the incident light reflected is given by [2]

$$\%\text{Reflected} = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \times 100$$

For air ($n \approx 1$) and glass ($n \approx 1.5$), about 4% is reflected from each surface. If n_1 is the same as n_2 (glass and oil) then no light is reflected.

Application

To minimize the amount of light reflected (and maximize the amount transmitted) the index of refraction (speed of light) in the incident and transmitting media should be as close as possible. Sometimes, "index matching fluids" are used, for example, when two optical fibers are joined in a temporary splice to minimize reflection back into the signal source.

A much more interesting application for many students is the gel applied before an ultrasound examination. Most students (and adults!) think the purpose is to make the transducer slide more easily over the skin. In fact, it is index- matching gel to maximize sound energy transmission from the transducer into the body.

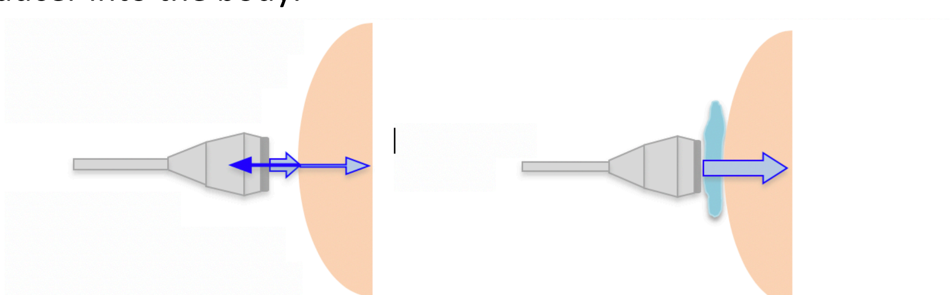


Figure 8. Left: Sound waves traveling from left to right are partially reflected at each surface where the speed of sound changes. RIght: Index (of refraction) matching gel between the ultrasound transducer and skin minimizes back reflection and maximizes the amount of energy entering the body.

#6 Amazing Jello®

Video: *https://youtu.be/wjEm45jlFrI*

Can you focus light with gelatin? Make a gelatin optical fiber? If you are really clever, can you make a graded index gelatin fiber?

This is another classic activity with a new twist. Younger kids can just observe the bending of light, older students can measure the index of refraction. Don't forget to talk about laser safety!

Materials

- Slabs (around 1.5 cm thick) of very stiff gelatin. You can use plain gelatin or flavored sugar-free. Just don't use the kind with sugar- it makes a sticky mess. *Spray the pan with oil to make it easier to remove the gelatin.*
- Something to cut with–knives work, but 2 cm wide strips cut from a plastic folder can be bent to shape and are less dangerous. Large round cookie cutters are also good for making "lenses"
- Laser pointer (the dollar store red ones are fine)
- Ruler and protractor if you want to take measurements
- Sugar if you want to try GRIN (graded index) gelatin (see below)

Procedure:

- Make the gelatin in a pan that will allow the gelatin block to be around 1.5 cm thick. If it's too thin it will be hard to handle. Use half the usual amount of water. On flavored gelatin packages, follow the recipe for "blocks" or Jigglers® (on the Jello® package). Remember to lightly oil the pan to make removal easier.
- To make in quantity, try asking the local butcher for some small plastic meat trays. It's easier to handle in small trays rather than in a large pan. If the gelatin is stiff enough it will not need refrigeration.
- Remove the hardened gelatin carefully and cut into shapes for experimenting. Long thin rectangles can be used to demonstrate total internal reflection (a gelatin optical fiber). Use a cookie cutter or thin flexible piece of plastic to cut "convex" and "concave" lens shapes.

Figure 9. Example gelatin shapes–rectangle, "fiber", lenses

- Make a gelatin optical fiber! Cut a long thin strip and shine the laser in from one end to illustrate total internal reflection.

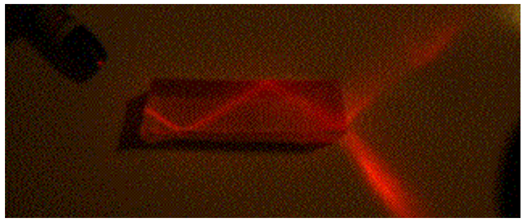


Figure 10. A gelatin "optical fiber" showing total internal reflection

- Advanced topic: While younger students can observe which way the beam bends (toward or away from the normal) as it goes from air to gelatin and back into air again, students with some knowledge of algebra and trigonometry can measure the index of refraction of gelatin. (This was one of several home-labs in a completely online introduction to optics course.)

  Draw perpendicular lines on a piece of paper and place the straight side of a gelatin block along one line as shown in Figure 10. Use a laser pointer to direct a beam into the block through the point where the lines meet. Mark the end of the laser and the spot at the edge of the block where the beam exits as shown. Remove the block to measure the angles of incidence and refraction and use Snell's law to calculate $n_2 = n_{gelatin}$ where $n_1 = 1$ (for air). Calculate n_2 using Snell's law

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

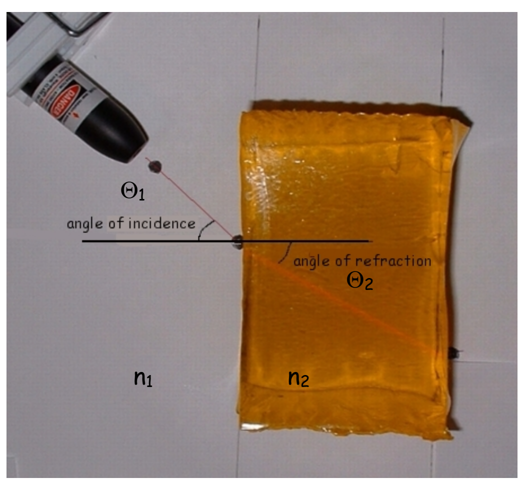


Figure 11. Measuring the index of refraction of gelatin . This photo shows lemon sugar- free gelatin. (We think yellow looks cool with a red laser.) Yes, the beam is drawn on the air side.

GRaded INdex gelatin (hat tip to Groot Gregory)

- Graded index materials have an index of refraction that changes throughout the material. The index of refraction of gelatin can be increased by adding sugar. To make GRIN gelatin, mix boiling water and gelatin powder as usual for gelatin optics. Then, add as much sugar as you can dissolve. You can make a slab or mold it in a cylinder, like a large plastic medicine container (Figure 12). Remember to coat the inside of the container with oil for easier removal.
- After the sugary gelatin has set, remove it from the container and cover it with cold water for a few hours. Sugar will diffuse out from the surface in contact with the water, resulting a gradually changing sugar concentration and thus, a gradually changing index of refraction, higher in the center and lower towards the edges.

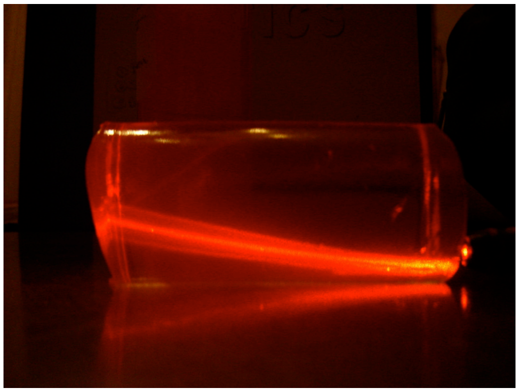


Figure 12. GRIN gelatin. This piece was made in a large (4.5 cm diameter) plastic prescription medicine container. The laser beam enters horizontally from the lower right and you can see it curves inside the gelatin due to the changing index of refraction.

How it works

We usually refer to the speed of light, not index of refraction, with fifth graders. When light goes from where it travels faster to where it travels slower, it bends toward the perpendicular line to the surface. If light goes from where it travels slower to where it travels faster, it bends away from this line. Light travels faster through air than it does through water, and faster in water than it does in glass.

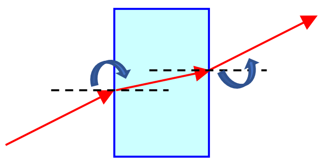


Figure 13. Refraction of a light ray as it goes from air to glass (blue) and back into air.

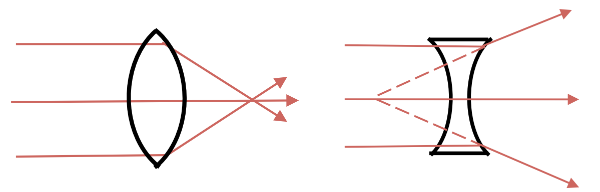
#7 The Misbehaving Lens

Uses watch glasses, not usually found around the house but common in chemistry labs

Video: *https://youtu.be/sY95YVHUp1E*

Can a double convex lens make light diverge?

Physics books often include diagrams like the one below, leading students to believe that a lens needs to be thicker in the middle to bring light to a focus. Is this always true?



Materials:

- Two watch glasses (from a chemistry lab)
- Silicone adhesive (the kind sold for aquarium sealing is good)
- A transparent water tank large enough to completely submerge the "lens". A fish tank or the small plastic tanks used for transporting fish or reptiles works well.
- A few drops of milk
- Laser pointer. If you have a laser ray box or a couple of laser pointers it works even better.
- Optional: A glass lens of similar in shape to the “air lens”, such as a large magnifying glass.

Procedure:

- Coat the edge of one watch glass with a thick bead of silicone adhesive/sealant. Carefully place the second watch glass on top, creating an air bubble between. Allow to cure thoroughly.
- Fill the tank with water and add a few drops of milk so that the laser beam is visible. Lower the "air lens" into the tank so it is fully submerged. (You will need to hold it in place–an air lens floats!)
- Direct the laser beam through the top, middle and bottom of the lens and notice where the rays travel after being refracted by the lens. Do they converge or diverge?
- If you have a glass converging lens, repeat the demonstration. Explain the difference!

How it works

As shown in Figure 13 above, light bends in a specific direction when going from air into glass and from glass into air. For a glass or plastic lens, light moves slower in the lens than in the surrounding air (or water). This causes light rays to converge to a focus beyond the lens. But light travels *faster* in an air lens than in the surrounding water so light rays behave exactly the opposite from a glass lens in air. Rather than focus, they diverge (spread out) as they leave the lens.

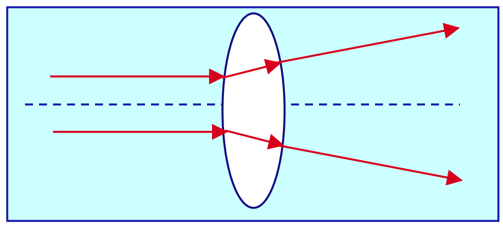


Figure 14. The "air" lens in a tank of water makes light coming from the left bend *away from* the axis.

The Misbehaving Lens: Application

How do swim goggles improve your vision? Your eyes focus light onto your retina, where sensors (rods and cones) detect the image and send the information on to your brain. (Figure 15) But most of the focusing is actually done by the cornea, rather than the lens, because lens power depends in large part on the difference in index of refraction of the lens and surrounding medium. The eye’s lens is surrounded by fluids whose index of refraction is not that much different from the lens.

Normally, the cornea is surrounded by air. However, when you open your eyes underwater, your vision is blurry because the difference in index of refraction between water and your eye is not enough to focus light on the retina- you become severely hyperopic (farsighted). (Figure 16) Swim goggles restore the air film in front of your eye and allow the cornea to do its job (Figure 17).

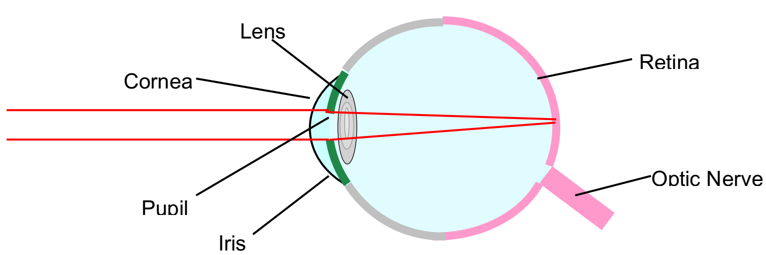


Figure 15. Normal eye in air. Most of the focusing power is due to the cornea.

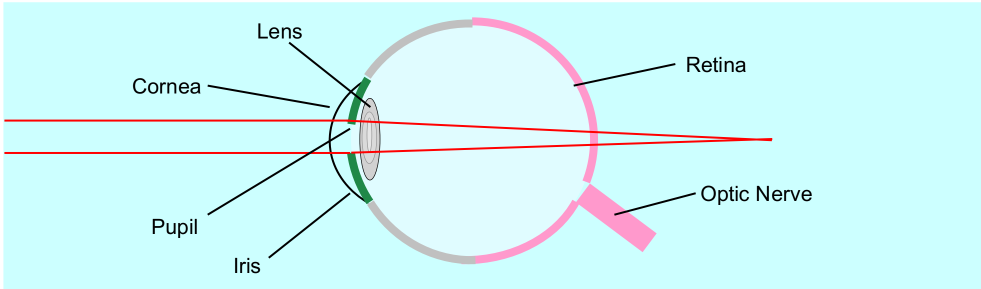


Figure 15. Under water, the index of refraction change between the medium and the cornea is reduced and light from a distant object focuses behind the retina. It's similar to being farsighted- everything looks blurry.

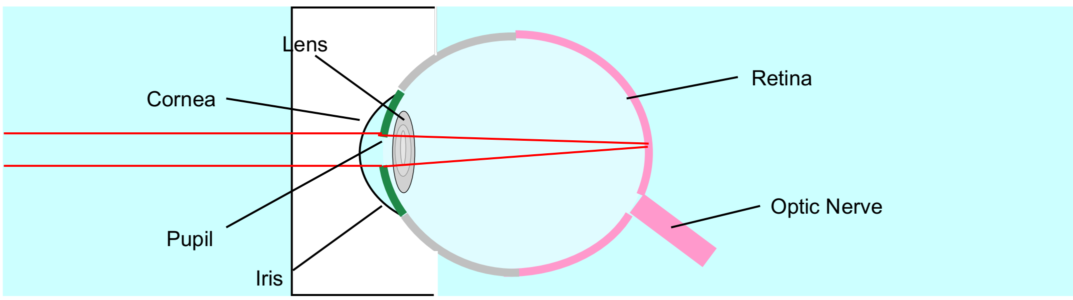


Figure 16. Swim goggles restore the air film at the cornea, allowing the eye to focus.

Polarization Magic

#8 The Magic Box

This experiment uses sheets of polarizing film. Sources to purchase are in the notes at the end.

Video: *https://youtu.be/MTp73BHUZd8*

Can you build a "wall" that solid objects can pass through? Where does the "wall" come from? How do objects pass through it?

This is a very cool illusion. Even people who know how it's done find it fascinating. The *Explorations in Optics* found at www.pblprojects.org includes an introduction to polarization that can be done with polarized sunglasses and a laptop screen;.

Materials:

- A cardboard box about the size of a tissue box.
- Four 2"-3" squares of polarizing film
- Tape
- Optional, for dramatic effect- a knife or chopstick

Procedure: (See Figure 17.)

- Cut out rectangles approximately 2" by 4" from both the front and the back of the box. Be sure that each opening can be completely covered by two polarizer squares when they are placed side by side. Carefully align these openings so you can look right through the box.
- 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. Tape the other two 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 17)
- Look through the front of the box. Where did the black wall come from in the center of the box? Optional: Poke a hole in the end of the box. Carefully stick a knife or chopstick into the box from the end- piercing the “wall” with no resistance!

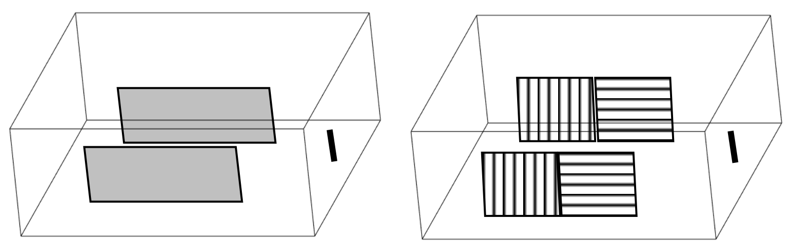


Figure 17. Construction of the Magic Box. Left: Cardboard box with rectangles cut out in the front and, directly opposite, in the back. Right: Polarizers mounted over holes, with transmission axes indicated. The slit on the end is optional, for piercing the “wall”’ with a knife or other long thin item.

How it works

This is easier to explain to fifth graders if they previously worked with some polarization activities. (The The *Explorations in Optics* experiment is a good introduction.) They then should understand that:

- Light is a wave that vibrates back and forth at right angles to the direction of motion.
- "Natural" or "randomly polarized" light can vibrate in any direction.
- Polarizing light restricts the vibration direction, for example, a horizontally polarized light wave vibrates only horizontally.

- A polarizing filter acts somewhat like a picket fence, only allowing one direction of wave vibration to pass.

  Suppose that natural light passes through a vertically oriented polarizer. (Figure 18) Only vibrations in the vertical direction pass through. What happens if this vertically polarized light strikes a polarizer oriented in the horizontal direction? This second polarizer cannot pass vertical vibration so no light gets through.

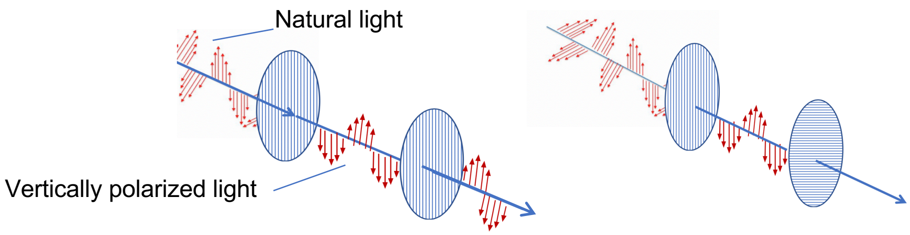


Figure 18. On the left both polarizers are vertical and light passes. On the right, the second polarizer is horizontal and light is blocked.

Look again at the "wall" in the magic box. Where the horizontal polarizers in the front of the box overlap vertical polarizers in the back of the box– even just a little bit– no light passes. This is what gives the appearance of a wall in the center of the box.

Application

Sunlight is randomly polarized; the light waves vibrate in all directions. However, when sunlight is reflected from a surface such as water or snow, it is polarized so that the vibrations are back and forth parallel to the reflecting surface. These vibrations can be blocked by a polarizing filter oriented perpendicular to this vibration direction. Polarized sunglasses block glare by preventing the polarized light from passing though.

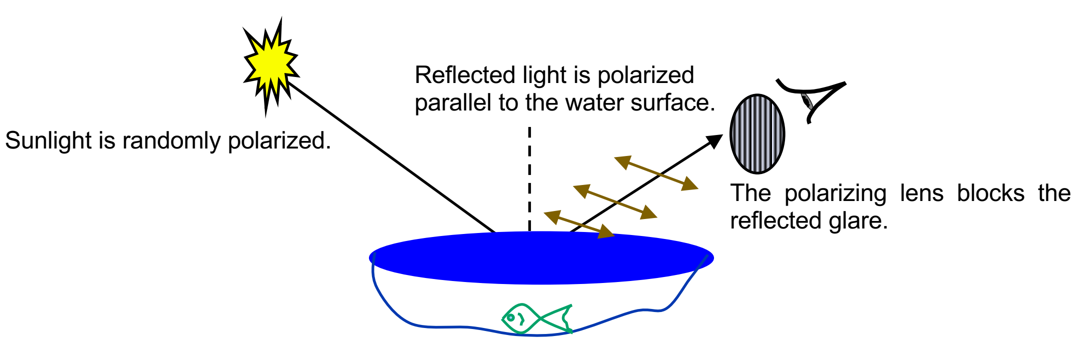


Figure 19. Polarizing sunglasses work because the reflected glare of the sun from water or snow is polarized. The polarizing film must be mounted in the correct orientation for the glasses to work.

#9 Polarized Light Art

This beautiful experiment can be done with polarized sunglasses.

Video: *https://youtu.be/8IdFUmgbB6M*

Video: *https://youtu.be/YE50rPWDF8w*

Can you make colorful art from plain old cellophane tape?

Clear cellophane tape is colorless. However, if it is placed between two polarizing filters, the tape can show brilliant colors. Where do the colors come from? Why do the colors change when the polarizer is rotated?

Materials:

- A laptop or tablet with LCD screen and pair of polarized sunglasses (you could also use two pieces of polarizing filter)
- Cellophane tape or other pieces of cellophane, for example, from vegetable or flower packaging
- A piece of clear plastic. You probably don't want to stick things onto your laptop screen.

Procedure:

- Place small pieces of tape or cellophane on the plastic film. (You can attach the cellophane with a glue stick.) Attach the tape or cellophane in different directions, and try varying the thickness.
- Choose a plain background (like an empty document) on the laptop screen. Place the film with cellophane on the screen. Put on the polarized glasses and take a look!
- Try turning your head (which rotates the polarizer direction in the glasses). What do you see?

How it works

Cellophane and other so-called *birefringent* materials can affect polarized light by changing the direction of vibration of a light wave. (Birefringent means light travels at different speeds in different directions of the material – bi = two and refringent = refracting.) For example, if vertically polarized light passes through a piece of cellophane, the direction of polarization will change. The exact amount the direction changes depends on the thickness of the cellophane and on the color (wavelength) of the light. Since different colors are rotated to different directions, the polarizer in the sunglasses "chooses" which color you see. (See Figure 20.)

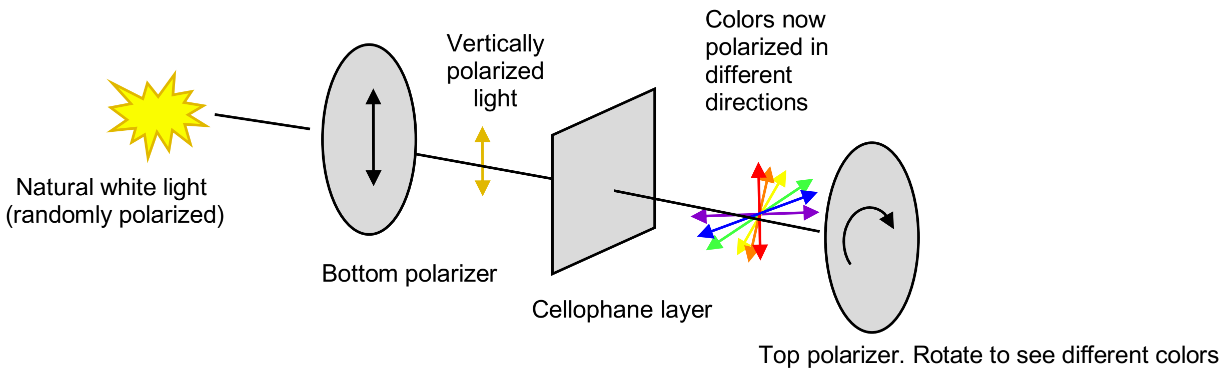


Figure 20. The cellophane rotates the direction of polarization. The amount of rotation depends on the thickness of the cellophane and the wavelength of light.

Application

This technique can be used to create beautiful works of art that change from one image to another as the top polarizer is moved. Austine Wood Comorow, who coined the term Polage®, creates wall-sized art for museums and other public spaces using polarized light. You can see demonstrations of her art and learn more at www.austine.com.

In technology, this effect is used to detect stresses in transparent materials. Plastic and glass behave similarly to the cellophane in this experiment when placed under stress. This principle can be used to detect stress in materials such as optical fiber as it's being manufactured. The eyeglass lenses in Figure 21 are subject to stress as can be seen in the right hand part of the photo where the lens is viewed in polarized light

Figure 21. These eyeglasses are resting on a light box covered with a sheet of polarizing film. A second piece of film oriented at right angles to the first is covering the eyeglasses on the right side. Stress in the glass lenses is apparent under the top polarizer.

Light You Can't See

#10 Fun with UV

These experiments require specialized, but not expensive, materials.

Video: *https://youtu.be/p0XaJEIDOjA*

How does ultraviolet light work? How do we know it's there if we can't see it?

This is a potpourri of fun activities to do with UV flashlights, glow-in-the-dark materials and UV reactive beads.

Materials:

- UV flashlight – see notes for where to buy
- Small flashlight
- Red and blue LED finger lights or other sources of red and blue light
- square of phosphorescent paper or plastic or other "glow in the dark" material – this can be a toy or even a tee shirt
- whitening detergent
- paper, preferably not white copy paper which is made with whitening agents that obscure the effect. We find colored sticky notes work well.
- cotton swabs
- UV color change beads – see notes for where to buy

Procedure:

- *Phosphorescence*: This works best with the room lights off, but it does not need to be really dark. Shine the flashlight onto the square of phosphorescent (glow in the dark) material and observe the glow after the light is removed. Predict what will happen if you shine the red and blue LEDs on the material, then test your predictions. Why doesn't the red light have any effect? Do you think a flashlight will work? Why?
- *Fluorescence:* This works best in a dark room. Use a cotton swab to write a "secret message" with the detergent on a piece of paper. Illuminate with the UV light. Does it continue to glow when the UV light is removed? Why not? How is this different from the glow-in-the dark material, which continues to glow when the light is turned off?
- *UV beads*: These can be illuminated with the UV light or just expose them to sunlight. Use the beads to test sunscreens! Choose a single color bead and dip some in sunscreen. Use different SPF factors if you can. You might also just cover some of the beads with different types

of fabric to see which ones are better at blocking ultraviolet light. Put the beads on a plate and leave some uncovered and some completely covered. Take all the beads out in the sunlight (or use a UV flashlight) and after a few minutes compare the color of the covered, uncovered and sunscreen or fabric protected beads.

Note: If the beads are hard to handle, they can be glued to popsicle sticks for ease of handling. Cover a pan with aluminum foil and place the beads flat on the foil. Put in a 300^{o}F oven for about 15 minutes until the beads are flattened. (They will look clear at this stage.) After the flattened beads are cooled they turn white again. At this point, glue them onto the sticks and proceed as above. The *Nanosense Project*[3] has complete instructions.

How it Works

Visible light is produced when atoms in a high-energy ("excited") level return to a lower energy level. Atoms and molecules 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 light energy quickly in which case it is called fluorescence. Or, the atoms may release light energy over a longer period of time, which is called phosphorescence.

The ultraviolet light waves used in this exploration have high energy. By comparison, blue light has lower energy and red light has lower energy still. Red light does not have enough energy to energize the phosphorescent material. The more energetic blue light can provide enough energy to excite the material, and then it continues to glow for a while. Why does the white light of the flashlight work?

UV beads don’t really fit in the “glow in the dark” category because they are neither fluorescent nor phosphorescent. Instead, they contain a polychromic dye molecule that changes shape when illuminated by UV light. The new shape absorbs visible light and so appears colored.

A note on the sunscreen experiment: The SPF factor on sunscreen bottles is a measure of UVB protection, but the UV flashlights are usually around 395 nm (UVA). UV beads respond to the relatively narrow range 300 nm-360 nm, which includes the high energy part of UVA (320-400 nm) and low energy part of UVB (280-320 nm). With older students this might lead to a discussion of the validity of using the beads and/or flashlights to test SPF of sunscreens.

Application

The detergent contains “whitener” that fluoresces when activated by UV light. This makes your white clothes look clean and bright in the sun. Certain toothpastes and eye drops are also fluorescent. Among other common fluorescent items are petroleum jelly and urine; in fact, some UV flashlights are advertised as “urine detectors.” Spelunkers carry UV flashlights to seek out scorpions, which glow under UV light (except when molting; only the hardened exoskeleton glows).

Some skin product companies sell a “skin analysis” UV lamp that reveals certain skin conditions (sun damage, dry or oily skin, etc) – all treatable with their own products, of course.

Finally, the common fluorescent lights in a classroom are coated on the inside with various florescent materials called *phosphors* that respond to UV light by emitting various wavelengths of visible light. The exciting UV light is produced by excited mercury atoms inside the tube. White LEDs can produce light in the same way using a blue or UV LED to excite phosphors to produce white light.

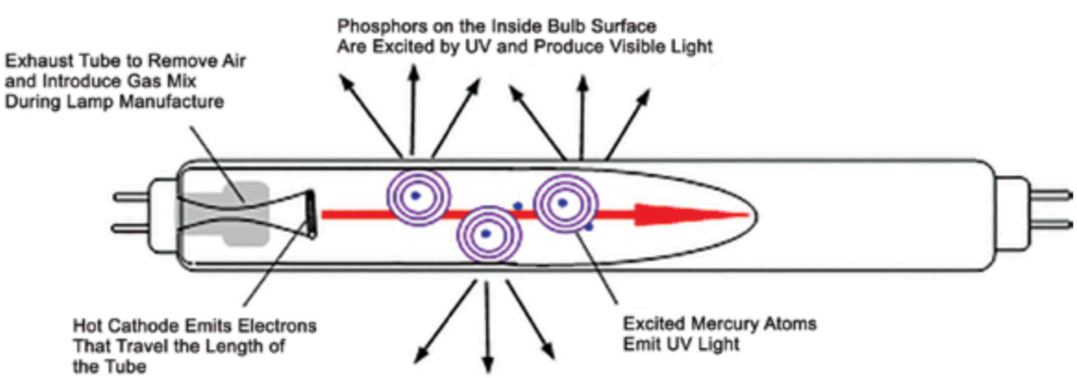


Figure 22. Cutaway diagram of a fluorescent light bulb. (from Donnelly and Massa, LIGHT – Introduction to Optic and Photonics, Laurin Publishing, 2018)

Sources for Materials and Notes on Alternate Procedures

The supplies for these experiments can be purchased from many sources; we list only one or two that we have purchased from recently.

1. *What color is a Tomato?* Inexpensive "finger" LEDs are available from a number of sources, including local dollar stores. Quality is not exceptional but can be purchased in boxes of 100 (25 of 4 colors) and they work well for these demonstrations. In a pinch you can stretch a balloon over a flashlight, but the light needs to be pretty bright for this to work. Experiment!
2. *Colors of Light.* This is a great way to use up all those CDs you recorded but now no longer need. Note that the labels on professionally produced CDs don't usually come off easily. If you prefer to use actual diffraction gratings they are inexpensive in large quantities from Rainbow Symphony Store (get the linear gratings for this experiment). www.rainbowsymphonystore.com If you'd prefer to buy cardboard tubes for a class (rather than have your friends and family collect them) 38 mm diameter mailing tubes are sold in boxes of 50 by a number of vendors. Check around for best price.
3. *Pinhole Viewer.* The best part of this activity is that there's nothing to purchase. A more durable pinhole can be made of a piece of aluminum cut from an aluminum soda can but it certainly isn't necessary. To make one, carefully cut the top and bottom off of the can (with scissors) and cut a piece about 5 cm x 8 cm. Be careful, the edges will be sharp! Round the corners to lessen the chance of an accident. We make a "drill" by sticking the blunt end of a needle vertically into a pencil eraser, then turning the pencil to drill the hole.

   Making an actual pinhole camera and taking pinhole photos is fun, but be sure to check on local regulations for silver-bearing waste disposal. We like Ilford brand black and white film paper and liquid developer and fixer, which are less messy than powders. We purchase from a local photography shop when we can but B & H Photo in New York city is also a good supplier (www.bhphotovideo.com).
4. *Amazing Bedazzled Kaleidoscope* We've tried many versions of inexpensive "personal size" kaleidoscopes but they seldom are as good as using actual mirrors. Plastic mirrors are expensive and the down-side to glass is evident. Here's a video showing how to assemble a kaleidoscope if you do have the luxury of small mirrors. This video shows how the kaleidoscopes are assembled from a mailing tube, plastic petri dishes and mirrors. (We bought a plastic mirror sheet and cut them to size with a laser engraver.) https://youtu.be/u7QzsSz80ak

   For a fun mirror target game to sharpen protractor skills, see the *Explorations in Optics* on the PBL Projects web site www.pblprojects.org .
5. *The Disappearing Beaker.* A pair of standard laboratory beakers works well but they usually have markings. If this is a problem, beakers with no markings can be purchased from Educational Innovations (www.teachersource.com). But first try whatever custard cups or measuring cups you have around the house.

6. *Amazing Jello.* We hit on gelatin as a material for introducing refraction because the clear plastic pieces made for the purpose are so expensive. The actual index of refraction of gelatin depends on the amount of sugar (if used) and water but it shouldn't be far from that of water (1.33). If you see a reference that states 1.6 it's probably wrong.
7. *The Misbehaving Lens*. Watch glasses are available from standard physical science suppliers. Most chemistry departments have plenty to share. Silicone adhesive can be found locally at stores that sell aquarium supplies or in home/hardware stores. For a water tank, we use a small pet carrier tank from a pet shop when a large aquarium is too large to work with. Large lenses can often be found at American Science and Surplus American Science and Surplus (www.sciplus.com). Another source of cheap lenses (and other optics) is Surplus shed (www.surplusshed.com). A local dollar store may have magnifying glasses that will work.
8. *The Magic Box* and *Polarized Light Art*. For inexpensive polarizing film (especially in quantity) try www.polarization.com. Polarization.com is also a great source of information on polarized light applications. You can also find small pieces of polarizing film at science supply houses like www.teachersource.com.
9. *Light you Can't See*. Phosphorescent vinyl is available in small pieces from a number of suppliers such as Educational Innovations (www.teachersource.com). Glow in the dark paper is less expensive and available from some craft shops. Or you could use a toy or piece of clothing that has a glow in the dark feature.

   UV beads are pretty easy to find, but our usual source is Educational Innovations (www.teachersource.com) which sells bags of 3000 beads (and includes information on how they work). They also carry UV flashlights. There are less expensive UV flashlights around, but some seem to be poor quality. Check local hardware stores and of course, Amazon.com

References

[1] Georgia State University Hyperphysics project, "Spectral Reflectance of a tomato", http://hyperphysics.phy-astr.gsu.edu/hbase/vision/spd.html

[2] Donnelly, J. and Massa, N. LIGHT-Introduction to Optics and Photonics,

[3] *Clear Sunscreen: How Light Interacts with Matter,* The NanoSense Project,
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