

# Optics Magic: Easy Explorations from the PHOTON Projects

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Photonics has been called a critical technology by the experts<sup>1</sup>, but for the students who have tried the hands-on activities in this workshop, photonics is just plain fun. Originally developed through PHOTON and PHOTON2, teacher professional development projects funded in part by the National Science Foundation, the PHOTON Optics Explorations have been field tested by over 100 middle school, high school and college teachers nationwide since 2000. The activities may be easily replicated in the classroom with inexpensive, commonly found supplies.

Key Words: light, optics, polarization, refraction, lenses

## 1.0 Introduction

The PHOTON and PHOTON2 projects of the New England Board of Higher Education were funded by the National Science Foundation's Advanced Technology Education program to develop materials and provide professional development for secondary and post secondary instructors to enable them to teach optical science and photonics technology. The PHOTON Explorations were developed from some of the favorite demonstrations of the project participants. They have been used to enhance fifth grade science activities as part of EASTCONN's Interdistrict program "Systems Explorers", with high school students in Three Rivers Community College's Laser Camp, and in secondary and post-secondary classrooms across the U.S.

### 1.1 *The "Magic" Explorations*

In each of the following Explorations, there is an element of "optical magic" to be explained. 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.

All of the Explorations are available for download at [www.photonprojects.org](http://www.photonprojects.org). The authors are in the process of creating a set of video demonstrations to assist teachers in performing the experiments; these will be available on Google video and through the [www.photonprojects.org](http://www.photonprojects.org) web site.

## 2.0 What color is a tomato?

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

Required materials: A small tomato, plum or tangerine work well. You can also use small colored candies and challenge students to correctly identify the color in order to "win" the candy.

At least two different color LEDs (light emitting diode) keychains or other colored lights. You could also use a flashlight, covering the end with blue, green or red transparent film. The goal is to create colored illumination.

Procedure: In a very dark room, hold the object (tomato, etc.) in your hand so that only a small portion of the surface is visible. Illuminate the object with one of the LEDs and observe the color of the illuminated surface. If you are unable to darken the room, place the object in a small box so that it is well shaded from ambient light. For example, a red tomato illuminated by blue light looks like a purple plum!

### ***2.1 What color is a tomato?: 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<sup>2</sup>. However, the skin is shiny so that when illuminated by a blue LED much of the blue light is reflected but no red light since the LED does not contain red light. Thus, the tomato looks like a blue plum.

### ***2.2 What color is a tomato?: Application***

Lighting plays an important role in marketing. Figure 1 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.



**Figure 1 - The wavelength content of a light source influences the perceived color of objects. (Photo taken at the Southern California Edison Lighting Center, 2004.)**

### **3.0 The disappearing beaker**

If transparent means that light passes through, how can you see a transparent object? Why does a window sometimes act like a mirror? Can a solid glass beaker disappear before your eyes? The disappearing beaker is a well-known but always effective demonstration.

Required materials: Two Pyrex<sup>®</sup> beakers (preferably without printing), a small one that fits completely inside the larger one, and inexpensive vegetable oil. Beakers or glasses of other types of glass may or may not work- experiment to find out!

Procedure: Begin by placing the small beaker inside the larger one, and noting that the inner beaker is plainly visible. Pour some oil into the smaller beaker; is it still visible? 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!

### 3.1 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, ambient light must reflect from the object so that it can enter your eye and be perceived. That is, a transparent beaker must reflect at least a small amount of light in order for you to see it. In the case of a transparent material like glass, wherever the speed of light changes, some light is reflected. Usually we talk about the index of refraction rather than the actual speed of light, where the index of refraction,  $n$ , is the ratio of the speed of light in a vacuum divided by the speed of light in a material. ( $n = c/v$ )

When light strikes glass head-on, the fraction of the incident light reflected is given by

$$\% \text{ of incident light reflected} = \frac{(n_{\text{glass}} - n_{\text{air}})^2}{(n_{\text{glass}} + n_{\text{air}})^2} \times 100$$

For air ( $n=1$ ) and glass ( $n=1.5$ ), about 4% is reflected from each surface.

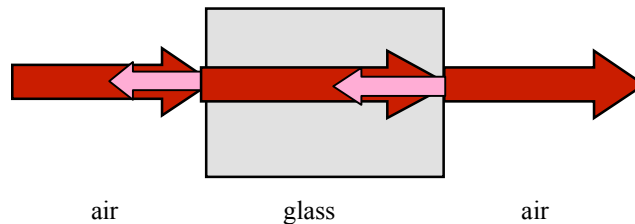


Figure 2 – Light traveling from left to right is partially reflected at each surface where the speed of light changes

The speed of light (index of refraction) is the same in the oil as in the beaker, so light is not reflected when there is oil surrounding both beaker surfaces. The speed of light does not change as light passes from oil to beaker and back into oil again.

### 3.2 The disappearing beaker: 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. Index matching gel is also used when two optical fibers are joined in a temporary mechanical splice connection to minimize reflection back into the signal source. Since sound is a wave, it is also reflected by surfaces. The gel applied to your skin before an ultrasound exam is also a type of index matching layer between the ultrasound transducer and your skin.

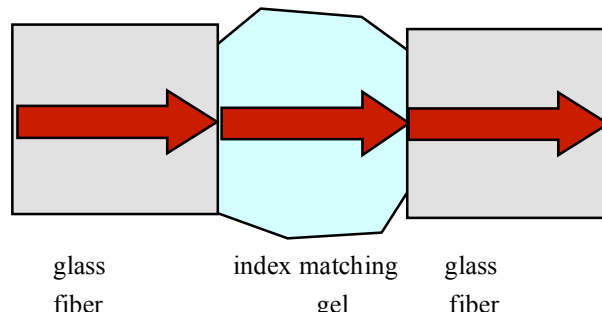


Figure 3 – Index (of refraction) matching gel between the ends of two glass optical fibers minimizes reflection

#### 4.0 The misbehaving lens

Physics books will tell you, “Lenses thicker in the middle bring light to a focus.” Is this statement always true? Is the lens shape the only thing that matters? Can a lens that is thicker in the middle ever make light spread out, rather than converge to a point?

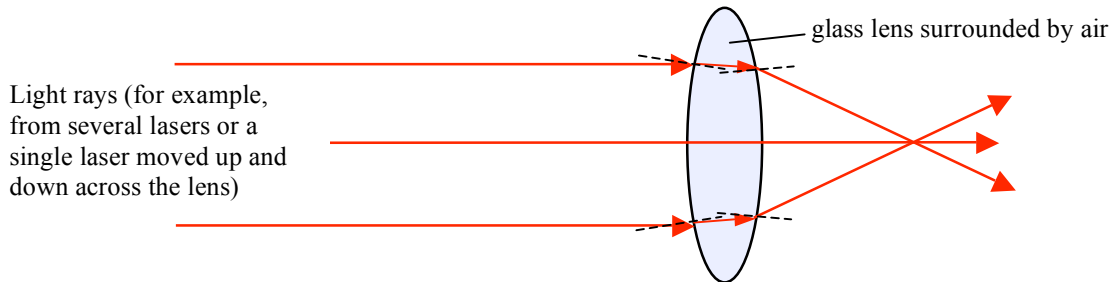


Figure 4 – A lens that is thicker in the middle brings incoming parallel rays of light to a focus.

Required materials: Two watch glasses (from a chemistry lab), silicone adhesive (such as sold for aquarium sealing), a transparent water tank large enough to completely submerge the "lens", a few drops of milk, laser pointer. Optional: A glass convex (converging) 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. (See Figure 6.) 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 that the lens is 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 come together at a focal point or diverge, that is, spread apart? If you have a glass converging lens, repeat the demonstration to show the formation of a focal point.

#### 4.1 The misbehaving lens: How it works

The speed of light changes as light goes from one medium to another. Refraction (bending of light) depends on the speed of light in the two media. If light goes from a medium where it travels faster to where it travels slower, it bends toward the normal (perpendicular) line to the surface. If light goes from a medium where it travels slower to where it travels faster, it bends away from the normal line. Light travels faster through air than it does through water or glass. (See Figure 5.)

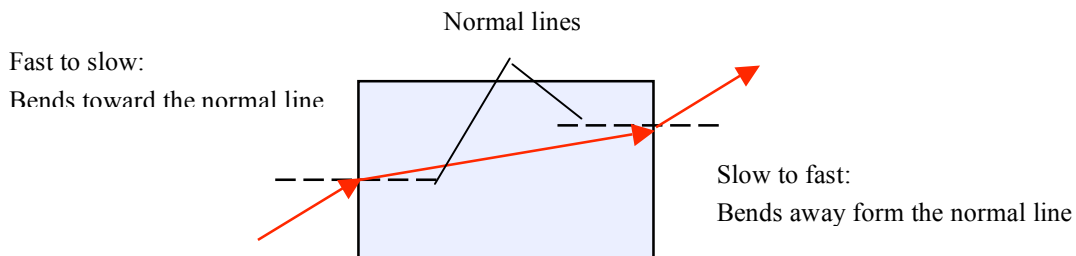


Figure 5 - Refraction of a ray of light as it goes from air (left) to glass (blue) and back into air (right.)

The usual situation for a glass lens is shown in Figure 4. Light travels slower through the lens than through the air that surrounds it. Refraction causes the rays of light that enter the lens from the left to be bent toward the center line, resulting in a common focal point. The "air lens" created by the air trapped between the two watch glasses causes rays of light to bend outward, away from the center line, because light travels faster through the air (in the lens) than in the water that surrounds it. We can neglect the effects of the watch glasses which have thin and parallel sides that do not appreciably bend light.

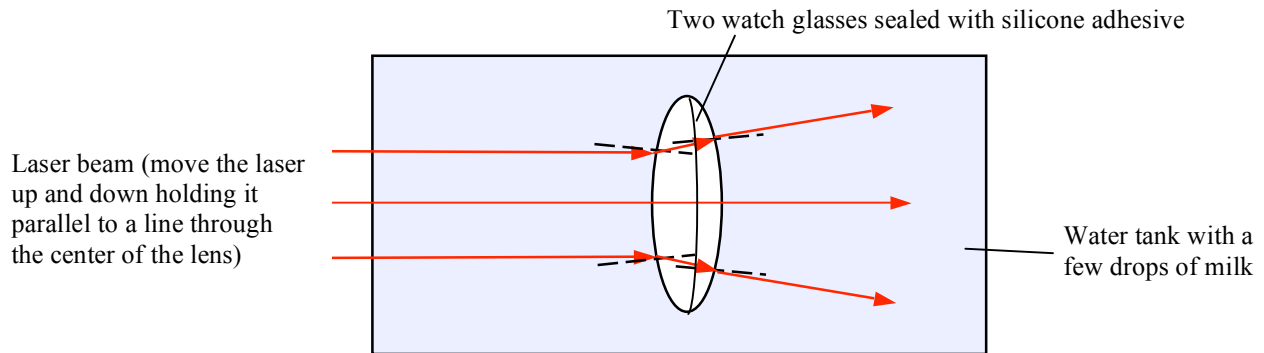


Figure 6 – The "air" lens in a tank of water makes light coming from the left bend away from the center line. Compare this to a "normal" lens in air (Figure 4)

#### 4.2 The misbehaving lens: Application

Although the speed of light is slower in plastic than in water, the speed of sound is *greater* in plastic than it is in water. This means a converging lens for sound is *thinner* in the center than at the edges. Such a lens can be used to focus sound from an ultrasound transducer (although there are other methods that are usually used for the purpose.)

Refraction, the bending of light as it travels from one medium to another, is used to explain a wide variety of optical devices made of glass or plastic.

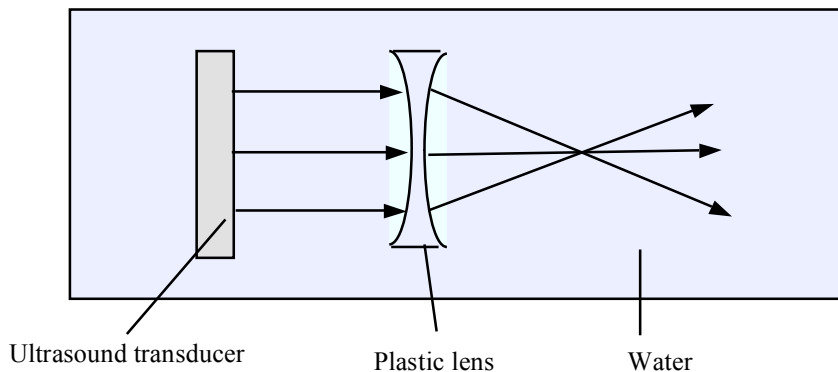


Figure 7 – A plastic lens to focus sound

## 5.0 The magic box

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

Required materials: A cardboard box about the size of a tissue box, four 2"-3" squares of polarizing film, tape. Optional: long knife or chopstick.

Procedure: Remove rectangles approximately 2" by 4" from both the front and the back sides 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 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.

Look through the front of the box. Where did the black wall come from in the center of the box? Optional: carefully stick a knife (or chopstick or other long, thin object) into the box from the end. It goes right through the "wall" with no resistance!

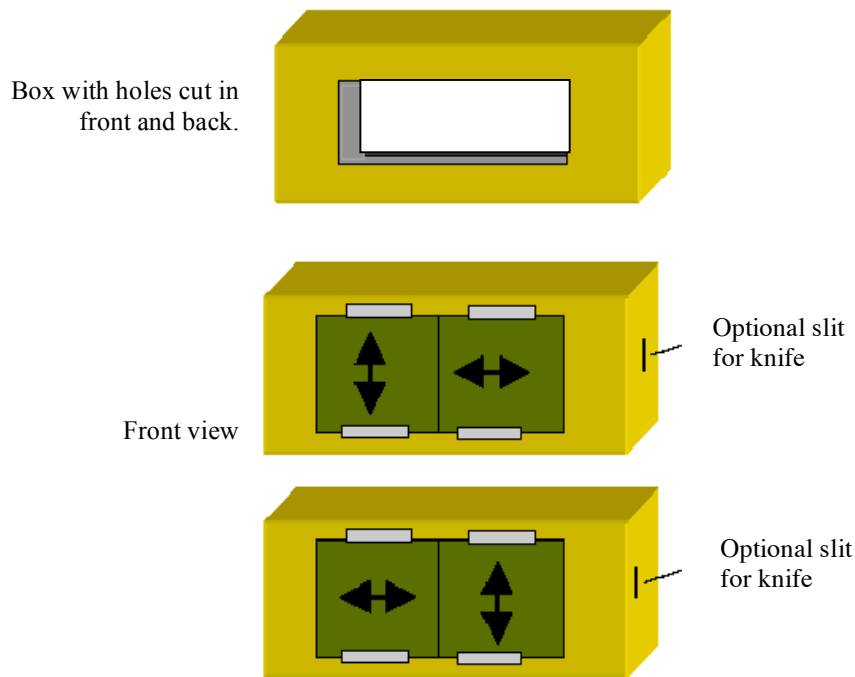
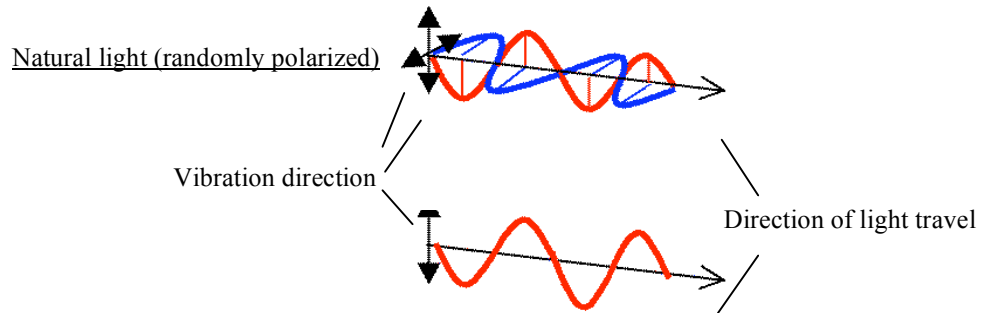


Figure 8 - Construction of the magic box. top: Box with rectangles cut in the front and back sides. middle: Front of box with opening covered with two polarizers. Direction of the transmission axis is indicated. bottom: Back of box with opening covered with two polarizers. Direction of transmission axis is indicated.

### 5.1 The magic box: How it works

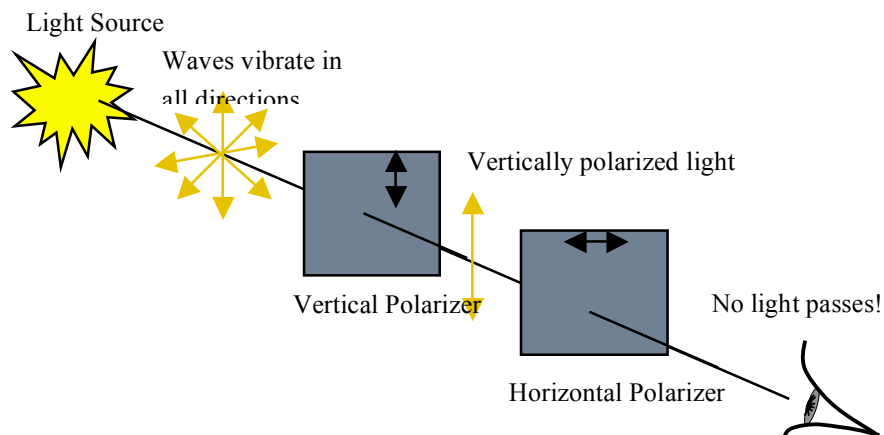
Light is a wave, vibrating electric and magnetic fields that vibrate back and forth at right angles to the direction of motion. (See Figure 9.) "Natural" or "randomly polarized" light allows vibrations in any direction. Figure 9 shows two of the possible vibration directions for the electric field. Polarized light restricts the vibration direction, for example, horizontally polarized

light has an electric field that vibrates only horizontally. Light can be polarized by reflection, by scattering, or by using “birefringent” crystals such as calcite. However, the easiest way to produce polarized light is with a polarizing filter, commonly called Polaroid® material. The material acts somewhat like a picket fence, only allowing one direction of wave vibration to pass.



**Figure 9 – (Top) Natural light may have the electric field vibrate in any direction perpendicular to the direction of travel; only two of these directions are shown. In a beam of polarized light, all of the waves vibrate in the same direction.**

Now suppose that natural light passes through a vertically oriented polarizer. Only vibrations in the vertical direction pass through, all the other vibration directions are absorbed by the filter. 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 10 – Two polarizers at right angles stop all light coming from the source from getting through to your eye.**

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 no light passes. This is what gives the appearance of a wall in the center of the box.

## 5.2 The magic box: Application

Sunlight is randomly polarized; the electromagnetic 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 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 through.

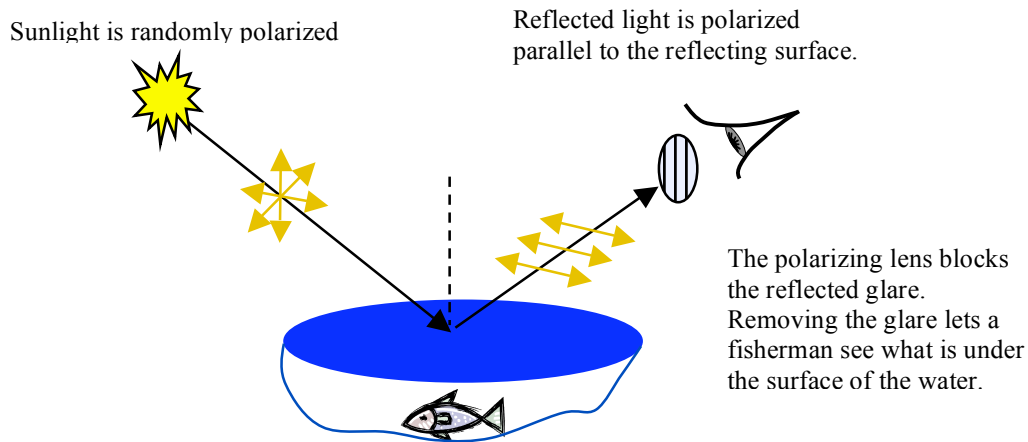


Figure 11 – Polarizing sunglasses work because the reflected glare of the sun from water or snow is polarized.

## 6.0 Polarization light art

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?

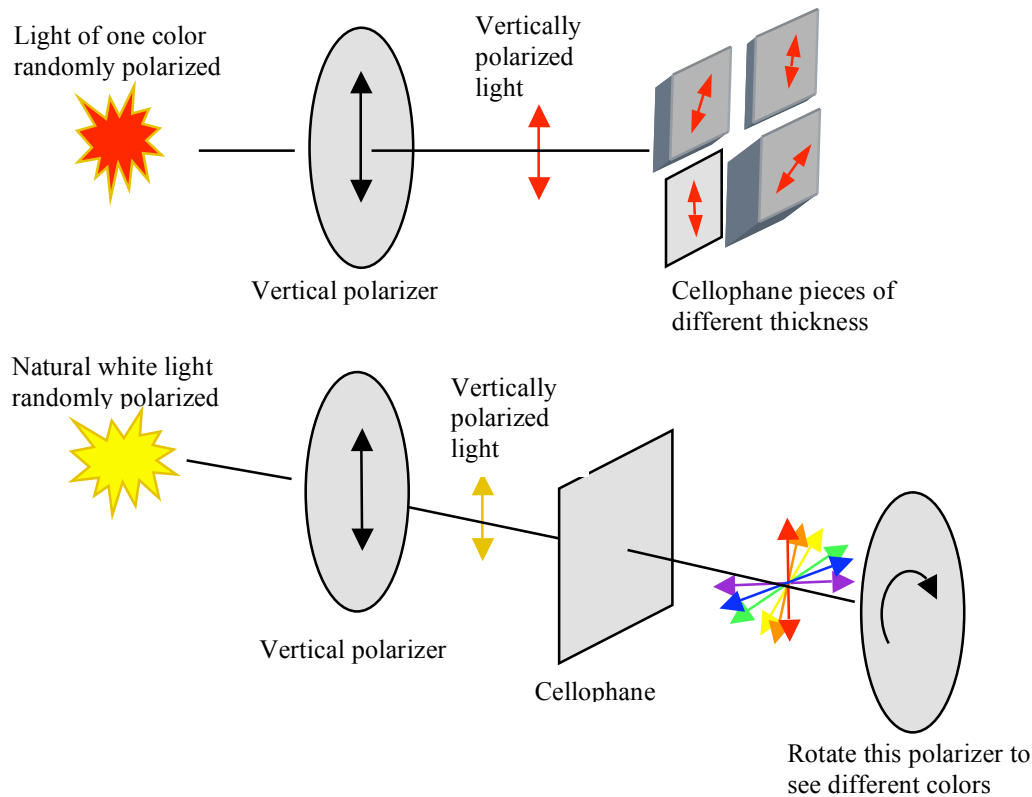
Required materials: Two squares of polarizing film, cellophane tape or other pieces of cellophane, for example, from packaging. To protect the polarizers, you can use a piece of clear plastic, such as transparency film, to hold the tape.

Procedure: Place one polarizing filter on a table, and place the clear plastic film over this. On the film, put small pieces of tape or cellophane. Attach the tape in different directions, and try varying the thickness of the tape. Place the second polarizing filter on top of the cellophane and rotate it, while you look through the polarizers and cellophane. In order to see the colors effectively, the polarizer-cellophane-polarizer stack should be back lit, for example, hold it up to a window and look through the layers. A photographer's light box works well too.

### 6.1 Polarization light art: how it works

Cellophane and other so-called *birefringent* materials can affect polarized light by changing the direction of vibration of the light wave. For example, if vertically polarized light passes through a piece of cellophane, the direction of polarization will be different on the other side. The exact amount the direction changes depends on the thickness of the cellophane and on the color of the light. The top polarizer passes light of a specific orientation. Since different colors are rotated to different directions, the top polarizer chooses which color you see.





**Figure 12 – In the top drawing, light of a single color is polarized in the vertical direction. After passing through pieces of cellophane, the direction of polarization is rotated. The amount of rotation depends on the thickness of the cellophane. In the bottom drawing, white light (containing all colors) is vertically polarized. The cellophane rotates the direction of polarization. The amount of rotation depends on the color, so rotating the top polarizer allows only one color to be seen.**

### ***6.2 Polarization light art: Application***

This technique can be used to create beautiful works of art that change 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. In technology, the effect is used to detect stresses in transparent materials. Plastic and glass become behave similarly to the cellophane in this experiment when placed under stress. Many naturally occurring birefringent minerals such as mica have a similar effect on polarized light.



**Figure 13 – 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. Stresses in the glass lenses is apparent under the top polarizer.**

## 7.0 Sources for materials

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

- What color is a tomato? Very bright (and expensive) PHOTON<sup>®</sup> LEDs are available from a number of sources, such as [www.photonlight.com](http://www.photonlight.com). They can sometimes be found at lower prices at sports and novelty shops.
- The disappearing beaker. A pair of standard laboratory beakers works well. Beakers with no markings that truly "disappear" can be purchased from Educational Innovations ([www.teachersource.com](http://www.teachersource.com)).
- 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.
- The magic box and Polarized light art. Sources for polarizing film include [www.polarization.com](http://www.polarization.com) (also a great source of information), American Science and Surplus ([www.sciplus.com](http://www.sciplus.com)), and Edmund Optics ([www.edmundoptics.com](http://www.edmundoptics.com)).

## 8.0 Resources and technical assistance

1. The PHOTON explorations are available at the New England Board of Higher Education web site, [www.photonprojects.org](http://www.photonprojects.org).
2. The PHOTON videos are available at the New England Board of Higher Education web site, [www.photonprojects.org](http://www.photonprojects.org).
3. Donnelly, J. and Massa, N. *LIGHT- Introduction to Optics and Photonics*, a general textbook on light and optics, available from <http://stores.lulu.com/photon2>
4. Photos of polarization light art and information on how it is created, [www.austine.com](http://www.austine.com)

## 9.0 References

1. *Harnessing Light: Optical Science and Engineering for the 21st Century*, Published by National Academies Press, 1998.
2. Georgia State University Hyperphysics project, Spectral Reflectance of a tomato, <http://hyperphysics.phy-astr.gsu.edu/hbase/vision/spd.html>