# Appendix:

## Light and Color

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The Light Around Us

I like to use this one to get us thinking. Most people think of sources from which light originates, like the sun, candles, light bulbs. Actually, anything you can see is a source of light, so you could categorize light as coming from things which produce light (the sun) and things which reflect light (the moon).

You can ask the question "where does the light come from" at another deeper level. Where does sunlight come from? The sun. But where does that light originate? It comes from nuclear reactions in the sun. How do the nuclear reactions produce light? Electrons in the sun gain energy in the reactions; when they release the energy, it is released in the form of light. I suppose you could categorize light producers as producing light by nuclear reactions (the sun), by chemical reactions (fire, fireflies), or by electricity (light bulbs); but in the end it usually comes down to electrons gaining energy from somewhere and later releasing energy in the form of light. This general statement even applies to reflected light.

Things which act as sources of light also produce heat. The sun, candles, and lamps all produce heat. Fluorescent lamps are "cool," but they still produce heat. Firefly light is very cool, but I am told it still produces heat.

Transparent, Translucent and Opaque

These are big words for elementary students, but they are good for categorizing practice. You can see images through transparent things. No light gets through opaque objects. Translucent objects let light through, but in such a way that sharp images are not formed. As is common in science, there are fuzzy boundaries where you are not sure which category an object should fall in.

Images

This is a consciousness raiser to make you aware of images which are formed in objects all around you, but which you often don't notice. Also, I have in mind categorizing images as reflected or transmitted, normal size or magnified (either larger or smaller), and right-side-up or upside down. You will notice that magnified images generally result from curved surfaces.

Pinhole Viewer

You can throw away your glasses, can't you. Actually, this isn't very practical for reading. The pinhole viewer is really just a pinhole camera. The pinhole camera explanation is given below.

If the pinhole camera image is upside down, why doesn't the pinhole viewer produce an upside down image? The answer is that the image is upside down, but the image is formed in your eye, where images are upside down anyway, and your brain knows to interpret an upside down image as right side up. The image on the pinhole camera viewing screen is also upside down, but when this upside down image is transmitted to your eye, your eye inverts it to make it right side up, so your brain says the image is upside down, which it really is. Yes, all of that really does make sense, if you think about it.
Pinhole "Camera"

Light travels in a straight line (although we will learn later there are exceptions). The only path for light to travel from the tip of the arrow through the pinhole to the viewing screen is shown on the diagram. Similarly, the only path for light to travel from the tail of the arrow through the pinhole to the viewing screen is also shown. The image formed on the screen will be upside down.

Do you think the image would also be reversed left-to-right? Can you observe and find out?

The One That Got Away

The image of the arrow appears to be at a shallower depth than the actual arrow. The image is called a *virtual* image because no light rays actually originate from it.

The virtual image appears because the light rays are *refracted* at the water-air interface. Refraction is bending of light at an interface between two different media. It occurs because the light actually travels at slightly different speeds in the different media.

Find the Coin

The diagrams on the next page show why the coin appears when you add water. Initially (top picture) if your eye is below the line running from the coin to the rim of the container, you can’t see the coin. You could think of the coin as being in the "shadow" of the side of the container.

When you add water, the apparent depth of the coin decreases, because the light rays bend when they pass from the water into the air. Since the coin appears to be at a shallower depth, you can now see it even with your eyes below the original lowest line of sight.

Once again, the image is *virtual* because no light rays actually originate from it.
If your eye is below this line, you can't see the coin.

Apparent depth is $d' = d/n$, where $n$ is index of refraction of water. If $n > 1$ (as it is for water), the coin appears to be at a shallower depth.

You can now see the coin below the "no see" line because the apparent depth is less. The heavier ray traces the actual path of the light.
How to Cut a Pencil with Water
Part 1

When you look straight through at the pencil, the light rays from the pencil above the water and the light rays from the pencil under the water follow a direct path to your eyes.

When you look slantwise at the pencil, the light rays from the pencil above the water follow a direct path to your eyes. The light rays from the pencil under the water are refracted at the water-air interface, and seem to have originated from a different point in space. There is no magnification.
Flat Mirrors

The image in a flat mirror is upright and normal size. Your brain might perceive the image as being larger or smaller than the object which generates the image, depending on whether your eye is closer to the object itself or to the image, but the image is really the same size as the object. The diagram shows how a flat mirror forms an image.

It is worth taking a little time to explain how the diagram to the right is generated. Imagine an object "O" standing to the left of a plane ("flat") mirror. Trace a couple of light rays from the tip of the object to the mirror and back. One light ray is shown going straight to the mirror and back, and the other light ray is shown going down and being reflected back at an angle.

Now, your eyes and brain think light rays travel in a straight line, so they trace an imaginary path of the light rays back behind the mirror. The two reflected light rays seem to have come from an image "I" identical to the object but behind the mirror. All light rays originating from the tip of the arrow and reflecting off the mirror will seem to have originated from the image in the mirror. Similarly, all light rays originating from any other point on the object will seem to have originated from a corresponding point on the mirror. The result is an image which your brain perceives as being "inside" or "behind" the mirror.

Notice that no light rays actually originated from the image. It is therefore called a virtual image, indicated by non-solid shading. The virtual light rays, which never really existed, are shown by the dotted lines. The path the light rays actually took are shown by the solid lines.

This same technique is used for explaining other kinds of mirrors as well as lenses, so it pays to figure it out with this simple example.

Most people think flat mirrors interchange right and left, because that's the way we are conditioned to looking at people. Flat mirrors really switch front to back. The explanation requires three-dimensional coordinate systems, and is probably high-school level material, so I'll skip it here. It's OK with me if you want to say a mirror reverses right and left.

Water Mirror

The bottom surface of water in a glass forms a very high-quality mirror. You need to have the glass sitting still, so the water is not sloshing around. If you look up from underneath, with a shiny spoon in the glass, you see a reflection of the submerged part of the spoon.

What you don't see is equally significant. From certain angles, you don't see through the water. Whatever is above the water is invisible. Light traveling the path AA' is refracted at the water surface, but gets through, but light traveling the path AB' undergoes total internal reflection and never gets out. The same holds for light going "out" to "in" the water. Light rays incident at an angle of 48° or less undergo total internal reflection. This is something for skin divers to think about.
The Hidden Coin

This activity is an example of an application of "water mirrors," or total internal reflection. It is also an exercise in logic.

You can see the coin from all angles (top and side) when there is no water in the glass. That means light can reach the coin, reflect off it, and travel to your eyes.

When there is water in the glass, you can see the coin from the top but not through the sides. Now, the index of refraction of plastic is greater than 1, and the index of air is 1, so the plastic in the "glass" we used (or the glass in real glasses) must refract the light as it travels from the coin through the glass and into the air. Obviously, this refraction does not prevent us from seeing the coin.

When the glass has water in it, you can see the coin from the top, but not through the sides. This shows that light does reach the coin through the water (otherwise you would not see it from any angle). Evidently the light reflecting off the coin may or may not reach your eyes, depending on where you place them.

The figure below is a slightly more detailed diagram of total internal reflection.

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Total internal reflection. The angle of incidence \( \phi_i \), for which the angle of refraction is 90°, is called the critical angle.
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Total internal reflection can occur only when light passes from one medium into another medium, where the second medium has a smaller index of refraction than air. Because the index of refraction of water is greater than 1 and the index of refraction of air is about 1, the total internal reflection must occur when light goes out of the water.
Curvy Mirrors

Let's start with the convex mirror, which is simpler. This discussion applies to spherical mirrors; mirrors which form part of the surface of a sphere. Take a look at the figure.

The point "C" is the center of the imaginary sphere; the mirror is part of this sphere. It turns out (and it's not hard to show in elementary college physics) that spherical mirrors always have a focal point, F, which is located halfway between C and the surface of the mirror. Notice the horizontal line which runs through the mirror and the points F and C. This line is called the central axis.

Consider an object, O, located on the mirror side of a spherical convex mirror. Let's trace three light rays coming from the tip of the object, and see where our eyes think they came from. The ray parallel to the central axis reflects off the mirror, and appears to have come from the tip of the image, along a line directed towards the focal point. The ray striking perpendicular to the mirror surface reflects straight back, and seems to have come from the tip of the image, along a line passing through "C." A light ray directed towards "F" reflects back along a horizontal line, parallel the central axis, and again seems to have originated from the tip of the image. These three rays, and in fact all other rays coming from the tip of the object, seem to have originated from the tip of the image, I.

Notice that no light rays passed through the mirror, and no light rays actually came from the image position. The image is a virtual one. The image in a convex mirror is always right side up, and always smaller than the object.

The above discussion really only works if the object is located an infinite distance from the mirror. If it is closer than that, all objects are, the light rays don't quite seem to have all come from the same point, and the image is slightly blurry. However, most objects are sufficiently far away for their images to appear quite sharp. A parabolic mirror corrects for this effect, and always forms sharp images.
Concave Mirrors

The two figures on this page show how concave mirrors can produce upright, reduced-size virtual images (when the object is farther away from the mirror than the focal point), and upside down, magnified real images (when the object is closer to the mirror than the focal point).

The figure below shows the production of a small real image. The image is real because light rays really do come to a focus there; you could put film where the image is and take a picture of it.

Concave lens, object outside focal point.

![Diagram of concave lens, object outside focal point]

C = center of curvature  
F = focal point  
= direction of travel of light ray  
○ = object  I = image

The figure below shows the production of a magnified virtual image. Light rays don't really come together at the position of the image, and if you put film at the position of the virtual image in the figure below, you would get nothing.

Concave lens, object inside focal point.

![Diagram of concave lens, object inside focal point]

C = center of curvature  
F = focal point  
= direction of travel of light ray  
○ = object  I = image
Concave Lenses

The image formed by a concave lens is always erect and always smaller than the object. The image formed by the lens is always a \textit{virtual} one. The image is also difficult to focus.

You may have heard of the term "focal length" of a lens. A concave lens has a \textit{negative} focal length. In contrast to convex lenses, which we will study next, the focal length is difficult to impossible to determine by direct methods. We won't discuss concave lenses much here, because they aren't of use in simple magnifiers.

The diagrams below show how a concave lens works.
Convex Lenses

The image formed by a convex lens may be inverted and smaller than the object, or erect and larger than the object. The erect image is a virtual one, and the inverted image is a real one. Light rays actually focus at the position of the real image.

You should have noticed that far away objects are smaller and inverted when viewed through the convex lens. When you bring the lens close to your eyes while still viewing the distant object, the image flips over and becomes magnified. The distant object is most blurry when your eye is at the focal point (a focal length away) of the lens. This is kind of confusing, isn't it.

The diagrams below show how a convex lens works. In the first diagram, the object is inside the focal point and the image is a virtual, magnified image.

In this case, the object is closer to the lens than the focal point.
The image is upright and magnified.

In the second diagram, the object is outside the focal point, and the image is a real image.

In this case, the object is farther away from the lens than the focal point.
The image is inverted and "shrunk" (magnification<1).

In this diagram, the object is very close to the focal point, so the image is almost (but not quite) full size. If you measure it, you will see the image is smaller than the object.
Mirror Draw

Try timing yourself while you trace these two simple, identical mazes, once directly and once looking in the mirror only.

Find the Magnifier

This is a variation on the "Images" activity. You may have noticed some of the images you found were magnified (smaller or larger). It generally takes curved surfaces to produce a magnified image. Magnified images are produced by objects that resemble either our curvy mirrors or our lenses.

Filters

Filters are designed to transmit only certain wavelengths (colors) of light. A red filter transmits red light, a green filter transmits green light, and a blue filter transmits blue light. A picture drawn in red on a white sheet of paper should "disappear" when viewed through a red filter, provided the red drawing is the shade of red transmitted by the filter. This happens because the white paper reflects all colors of light; if only red gets through the filter, you can't make out the drawing. Later on we'll see how good our filters are.
Streetlamp Spectroscope

Because light is a wave, it bends around corners. The different colors of light, having different wavelengths, bend to different angles. The "plastic" diffraction grating has thousands of grooved lines ruled in each inch; each of these lines acts as a corner to bend light. There are enough "corners" in the diffraction grating to produce a visible spectrum.

Light from atomic gases arises from electrons changing their energies by fixed, discrete amounts. When electrons lose energy, they emit light. The color of light emitted by atoms and molecules is a unique "signature" of their presence. We use diffraction to find out what is in distant stars and what is in earthly samples of unknown materials.

How Green Is Your Blue?

We can use our filters in conjunction with our spectrosopes to see how good our filters are. Look at a white light through the spectroscope. Then put the filter in front of it. You should "see" missing colors from the resulting spectrum. The missing colors are the ones that are filtered out.

You will observe that our filters really transmit a range of colors instead of just a single color. However, the "red" filter mainly lets red light through, and the "green" filter mainly lets green light through. On the other hand, the "blue" filter lets both blue and green light through.

Red, green, and blue are the three primary colors out of which all other colors can be made. I would expect the company which made the filters I bought to supply filters for each of the primary colors. They did for red and green (more or less) but not for blue.

On the other hand, printers make colors using the CMYK system. CMYK stands for cyan, magenta, yellow, and black ink. Cyan, magenta, and yellow can also be used to produce all possible colors. The black ink is used to make blacker blacks. Cyan is a combination of blue and green. Our "blue" filter is therefore really a "cyan" filter.

Polarization

Light is an electromagnetic wave which exhibits polarization: the electromagnetic waves making up light rays "vibrate" in planes perpendicular to the light's direction of propagation. In the figure, the wave on the left is polarized in the vertical plane, and the wave on the right is polarized in the horizontal plane.

Light emitted by most sources is "unpolarized." That doesn't mean the light has no polarization; instead, it means that the light is randomly polarized. Light waves from a light bulb or fluorescent lamp have equal probability of being polarized in all possible planes of orientation.

Polaroid material is simply a special filter which transmits only the component of light polarized in a particular plane. Think of it as a "picket fence" for light. If light vibrates in parallel with the "fence," it can get through.

Two sheets of polaroid, one on top of the other and oriented the same, will let light through. Rotate one 90°, and the "picket fences" are crossed, and whatever gets through the first sheet can't get through the second.

Single sheets of polaroid are useful for cutting down glare light, which is polarized when it gets reflected. Multiple sheets of polaroid are useful for observing stresses in materials.
A Different Kind of Lens

Most lenses are made of glass or plastic, and have curved, rather than flat surfaces. The curved surfaces are necessary to refract light in a manner so that an enlarged (or shrunk) image is created.

You have been given another kind of magnifier, one which is flat. If you examine it, you can see concentric circular patterns of grooves. Remember how light is bent by edges? There are lots of edges in diffraction grating. There are also lots of edges in the sheet magnifier, designed in a pattern to produce a magnified image.

Why doesn't the sheet magnifier split the light into its component colors? Actually, it does, but it is not as effective as diffraction grating, so you don't notice it as much. Actually, it takes a lot of work to make a lens produce a magnified image without splitting the light into its colors; such lenses are much more expensive than the ones we gave you (which are expensive enough).

Where are sheet magnifiers used? Overhead projectors is one place that comes to mind. Any place you need a large but cheap lens is a candidate for a sheet magnifier.

Christmas Tree Ornaments

We all have Christmas tree ornaments, but probably never really look at them. Good ornaments are nearly spherical, and are good reflectors. Silver ones work best.

Someday, look into a spherical silver ornament, and notice how you can see almost all of your surroundings in it. You can even see things in front of you. In fact, you can see in it anything which doesn't fall in the "shadow" of the ornament. Things to the front of you tend to be highly distorted.

You can easily pick out nonspherical portions of the ornament by looking at the image of a straight vertical object. The straight object will be noticeably distorted where the ornament is nonspherical.

Ornaments are good for looking around corners, under tables or disks, and in cramped places you can't easily get to.

Hold two ornaments close to each other, and look at the multiple reflections inside reflections.

Ornaments make a delightful sound when they shatter. Someday I'll have to tell you the story of my twin boys and the Christmas tree.
Materials Needed

Materials Needed To Do Light Activities:

index cards or small pieces of paper
pin
black construction paper
can or box (Pringles can, coffee can, shoebox)
pair of tall glasses
thumb tack
nail
waxed paper
tape
paper clips
coins
water
shallow bowl
pencil
flat-sided transparent water container (e.g. aquarium)
clear glass or plastic glass
flat mirrors
clothespins
large shiny spoon
concave mirrors
convex mirrors
book or book-sized box
concave lenses
convex lenses
white paper
prism
red filter
blue filter
green filter
colored markers or crayons
TP or PT tube (toilet paper or paper towel)
scissors
diffraction grating
streetlamp spectroscope
light sources
bright white light source
polaroid material
LCD display (watch or calculator)
Fresnel lens (flat magnifying sheet)
Christmas tree balls
Have Participants Bring:

- pringles/quaker oats can
- black construction paper
- 2 tall identical glasses
- large shiny spoon
- compact disc
- toilet paper/paper towel tube
- LCD watch/calculator

Instructor Provide or Set Up:

- bright white light(s)
- discharge lamp sources
- clear plastic cups
- maybe clothespins for mirror draw
- atomic emission chart
- shallow bowls