Physics 145: Geometric and Wave Optics

What's the point?: Optical phenomena are an important part of many experiments, and often require only simple equipment. Here, you will explore some of the properties and behaviors of light (wavelength, polarization, reflection, refraction, and standing waves) and several basic optical devices and techniques (objects and images, lenses and mirrors).

Equipment: Part I (desk lamp, optical bench with lens holders, lens and mirror set, large and small magnification scales). Part II (microwave generator and detector with digital multimeter, microwave polarizer, microwave reflector with tape measure, curved microwave mirror, microwave prism).

Introduction: Briefly exploring the *Hyperphysics* website (do a Google search) section on *Light and Vision*. Note the links to topics such as *Reflection*, *Lenses* → *Lens Equation*, *Mirrors* (click the blue box), and *Prisms*. Start by reading about the **lens equation:** $\mathbf{1/d_o + 1/d_i = 1/f}$, which relates the location of a focused image (d_i), the location of the original object (d_o), and the **focal length** f of the lens. The lens equation also works with spherical mirrors, where f is equal to half the radius of curvature of the mirror. If you are concurrently enrolled in Physics 123, you can also refer to your textbook. Become aquainted with the shape and appearance of convex and concave mirrors and lenses. Note that the quantities in the lens equation can be positive or negative depending on which side of the lens they are located. Here are a few important sign conventions that will be useful later.

a) Focal length: convex lens (+), concave lens (–), convex mirror (–), concave mirror (+)
b) Object: (+) is always the source side.
c) Lens: image on source side is virtual (–); image on far side is real (+).
d) Mirror: image on source side is real (+); image on far side is virtual (–).

Then spend 10 minutes or so exploring a variety of lens and mirror focal lengths (positive and negative) using the *Optics Bench Physlet* resource created by Davidson College (go to http://webphysics.davidson.edu/Applets/optics4/default.html). Insert objects and find the relative sizes and locations of the resulting images. Insert point sources and parallel light sources (i.e. beams) and see how lenses and mirrors affect them. Simple instruments containing a single lens or mirror produce an image that may not have the same size as the original object. This **lateral magnification** is computed as $\boldsymbol{m = -d_i/d_o}$. For instruments containing more than one lens, **angular magnification** is also an important concept -- by magnifying the angular width of an object, a telescope or microscope makes an object appear closer than it is.

The geometric optics portion of this lab (Part I) will allow you build and characterize simple optical devices. No previous exposure to optics is required here because the concepts and the math are both quite simple. The wave optics portion of the lab (Part II) reveals that microwaves have much in common with visible light, while also permitting a direct measurement of the wavelength. Because of their convenient **wavelength** range (millimeters or centimeters), **microwaves** allow one to build intuition that isn't possible with **visible electromagnetic radiation**.

PROCEDURE (Part I - Geometric Optics): First, complete exercise A. Then choose at least two additional exercises, which may require repeating exercise A on other lenses or mirrors.

A. Determine the focal length of a positive lens or mirror. The focal length of a positive mirror or lens is the distance from the lens center or mirror surface to the point where parallel light rays converge. How can you obtain a beam of parallel light rays? You can also use the sun or a far-away lamp to obtain approximately parallel rays.

B. Experimentally verify the lens and lateral magnification equations for a positive lens.

C. Explain the formation of a real image using a positive mirror. Visit the "Illusive Dollar Bill" display in the lobby of the Eyring Science Center (just south of the Foucault Pendulum) where you will see the full-sized image of a dollar bill sitting on top of a pedestal. Read the comments posted on the front of the pedestal, and explain how the image is different from what you expect from an ordinary flat mirror. In the lens equation, is the image location of the dollar bill positive or negative for this display. Would the image location be positive or negative in the case of a flat mirror? Why is the image of the dollar bill upside down? Does this have anything to do with the minus sign in the lateral magnification expression? How could one obtain an upright image instead?

D. With a positive lens of focal length f, what is the minimum possible distance between an object and its real image? Hint: use a lens with a fairly short focal length, and move the lens between the object and a screen to find an image at two locations of the lens. Then move the screen closer and repeat the procedure to experimentally determine the answer to the question. The theoretical limit is $4f$. Explain this result in terms of the lens equation.

E. Create a simple telescope and show that its angular magnification is $m = -f_{obj} / f_{eye}$. Here, f_{obj} and f_{eye} are the focal lengths of the objective and eyepiece lenses, respectively. A high angular magnification is obtained by using a short eyepiece focal length and a long objective focal length, and arranging the lenses so that they share a common focal point. Try using a few different lens combinations to read some small print from across the room. With a little practice you can simultaneously look through the telescope with one eye and past the telescope with the other and let your brain superimpose the images for visual comparison. The large scale on the wall should help.

F. Determine the focal length for a negative lens. For a lens or mirror with a negative focal length, initially parallel incident rays appear to diverge from a virtual image located at the focal point on the negative image side. Hint: to make this measurement, you will need an auxiliary positive lens of known focal length (must be larger than that of the negative lens being tested) that will cause parallel light to converge at the focal point on the far side of the negative lens, thus becoming parallel again. When the separation distance d between the two lenses is adjusted to create this condition, then you know that $f_{\text{neg}} = -(f_{\text{pos}} - d)$. It may help to try this first using the OpticsBench Physlet mentioned above.

PROCEDURE (Part II - Wave Optics): Note: Complete A and B below. Exercises C and D are optional but quite important. **CAUTION -** Do not put the detector closer than 12 inches from the source. Do not place the metal sheet close to the source.

A. Explore the polarization state of the microwaves being emitted by the generator. A beam of electromagnetic radiation is said to be linearly polarized if the electric field of the beam has a well-defined direction. Your microwave detector measures the potential difference (i.e. voltage) between the ends of a small antenna, and responds most strongly when the antenna is parallel to the polarization direction. (1) Vary the antenna orientation to determine the polarization direction. Do you find the microwave polarization to be transverse (i.e. perpendicular to the beam direction) or longitudinal (parallel to the beam direction)? (2) Use a stand to fix the antenna parallel to the microwave polarization direction, insert the polarizer into the beam between the source and the antenna, and vary the polarizer angle. Verify that the signal detected is proportional $\cos^2(\theta)$, where θ is the angle of the polarizer relative to the maximum intensity positon. Can you explain the effect of the wires? (3) Set the antenna direction perpendicular to the microwave polarization and also perpendicular to the beam direction, which should yield a zero signal. Now try slowly rotating the polarizer again. What do you observe? Can you explain it?

B. Measure the wavelength of the microwave radiation. Set up a standing wave by reflecting the the microwave beam from a metal sheet back towards the source. Place the metal sheet at least 60 cm from the source, and place the detector, which should be oriented parallel to the microwave polarization direction, close to the metal sheet. You should see a series of peaks in the detected microwave intensity when scanning the detector towards the source, where two adjacent peaks are separated by half a microwave wavelength. Mounting your detector on the optical bench may make it easier to maintain proper position and alignment while scanning. Adjusting the position of the metal sheet slightly may also improve the contrast of the peaks. Now measure the wavelength. To improve accuracy, you can measure the distance that spans five peaks and divide accordingly.

C. Show that microwaves can be focused. Using a large curved sheet of wire mesh as a mirror (radius of curvature ~ 120 cm), focus the microwaves to a point somewhere between the mirror and the source. Do some simple calculations before hand to avoid placing the focal point at the source, which could damage the source. You may need to put your equipment on the floor in order to achieve a large enough source-to-mirror distance. The focal spot is about 2 inches in size -- scan your detector around until you find it. Mounting the detector on a stand will help with stability.

D. Refract microwaves through a paraffin prism. The **speed of light** inside a material is equal to c/n, where c is the true speed of light in vacuum, and n is the material's **index of refraction**. Because the speed of light is slower in the paraffin than in the open air, the prism should change the direction of the beam. Start by placing the prism so that the beam passes roughly through the middle of the prism, while keeping one face parallel (not perpendicular) to the beam. Then try to adjust the prism orientation so that incident angle (between the incident beam and incident face normal) equals the exit angle (between the exiting beam and the exit face normal). Use the Hyperphysics Prism tool to calculate the index of refraction n of the paraffin (measure δ, estimate σ, and assume $n_0 = 1$ for air). Approximate results are fine here -- don't worry too much about accuracy.