Introduction

In this lab we will consider optical systems that refract light in order to create images, as opposed to mirrors that reflect light rays.

For the following activities, you will use two physics simulation programs. Visit: https://uglabs.physics.ucr.edu/ for lab downloads and links.

First let's consider a flat sheet of glass. Parallel light rays will not be bent after passing through a thin flat sheet. This may seem trivial to point out here, but as we shall see, all lenses have a "flat" part to them in the middle.
Our working definition for what a lens is this: it is any refracting object that will focus parallel light rays to, or from, a focal point. Whether this flat piece of glass is considered a lens or not is a matter of semantics. A lens will have two focal points, and a useful convention is to call the one on the side where light enters the lens the near focal point; then the far focal point is located on the side where light exits the lens. Since lenses are symmetric objects, both focal points will be equally distant from the center of the lens.

If we consider here lenses surrounded by air or any material with a lesser index of refraction than the lens material, then a converging lens of glass would have convex-shaped sides. Parallel light rays entering from the left will converge to the far focal point on the right. Since lenses are symmetric objects, and paths of light rays are reversible, we can also state that light rays diverging from the far focal point on the left will be bent into parallel rays on the right.

Again, considering a lens surrounded by air, a diverging lens of glass will have concave-shaped sides. Parallel light rays entering from the left will diverge from the near focal point on the left. Conversely, light rays converging to the far focal point will be bent parallel.

So how do we find the images produced by lenses using a ray tracing? For any type of lens, there are three types of rays (called principal rays) that originate from an object that will be easiest to trace to find an image. While the specific choice and use of these rays may seem a bit arbitrary at first, these rays follow
naturally from the focusing (or defocusing) properties of the converging (or diverging) lenses discussed above.

The first ray to trace will come from the object and pass through the center unbent. This is because flat sheets of glass will not change the direction of light rays that pass through them, and that the center of a converging lens or diverging lens looks flat.

The second ray to trace is a light ray that comes from the object parallel to the center axis of the lens. For converging lenses, this ray will be bent inwards to pass through the far focal point. For diverging lenses, this ray will be bent outwards to diverge from the near focal point. Our eyes will naturally trace back this light ray as a virtual ray, because our visual processing systems always assumes that a light ray has always been traveling straight.

The third and last ray to trace is a light ray from the object that will eventually leave the lens parallel. This one is a little tricky. We note that for converging lenses, if the ray passed through the near focal point, then after passing through the lens, it will be bent parallel. For a diverging lens, if it is initially converging to the far focal point, then after passing through the lens, it will be bent parallel. (Don't forget to trace back the virtual ray here, too.)
Lenses

One item to note here – when we do ray tracings for lenses, we use the symbols at right for converging and diverging lenses. These symbols reinforce the idealization that we are using a model of "thin" lenses, that is, where the effect of the thickness of the lens is negligible. The top symbol represents a converging lens and the bottom symbol represents a diverging lens.

Rather than locate images using the geometry of the three principal rays this geometry can be turned into an algebraic expression. The result is the thin lens equation, which assumes a lens with thickness small compared to all other relevant distances. This mathematical expression is given by:

\[ \frac{1}{s} + \frac{1}{s'} = \frac{1}{f} \]  

where \( s \) is the distance from the object to the lens, \( s' \) is the distance from the lens to the image, and \( f \) is the focal length of the lens (\( f > 0 \) for converging lenses, \( f < 0 \) for diverging lenses). If we know any two of the distances \( f, s, \) or \( s' \), we can use the thin lens equation to find the third distance. It is always good practice to sketch a ray tracing as well, because it is easy to make mistakes with the negative signs in the thin lens equation.

Following the sign convention (±) for these parameters is important for you to properly utilize the thin-lens equation. The diagram to the right shows the regions with respect to the lens in which \( s \) and \( s' \) are either positive or negative. Note that the sign conventions for the thin-lens equation are different than those for the mirror equation.

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Also, we can define a linear magnification $m$ which tells us how large (or small) the image ($h'$) is compared to the original object ($h$), and whether the image is upright (+) or inverted (−), depending on the sign of $m$:

$$m = + \frac{h'}{h} = \left( \frac{s'}{s} \right)$$

A real image results from the actual intersection of light rays while a virtual image results from the apparent intersection of traced back light rays. In lab, you may notice that since you can see either type of image with your eye, you cannot tell the difference between them without additional perception cues. However, a real image can be seen on a screen held at the location of the intersecting light rays, while a screen cannot be held at the location of a virtual image (as there is no actual intersection of real light rays there).

Rays form an image that is indistinguishable from rays coming from an object. Hence, a second lens can make an image from an image (either real or virtual) produced by the first lens. This is the motivation behind wearing glasses. Glasses help people by producing images of images. What this does is to assist us in changing the effective curvature of our (glasses + eye lens) systems. We first consider the general case of two lenses that are spaced apart; and then the special case where they are touching, and thin enough to be considered as effectively one lens.

Suppose we consider two lenses that are separated by a distance $d$:

We would first locate the image produced by the first lens by drawing the three principal rays: 1) Straight through the middle; 2) Parallel → through the far $f$; and 3) Through the near $f$ → parallel. (See examples below).
Then this *image* becomes the *object* for the second lens. Like our eyes, the second lens does not care whether the rays of light from the object it "sees" is from an actual object, or from an image (real or virtual). Remember that the object for the second lens has already taken into account the effects of the first lens, so we now ignore the first lens from here onward, and we draw the three principal rays for the second lens. (Note that the image distance from the first lens is not the object distance for the second lens).

### 1. Using Ray Diagrams to Predict Image Location

1.1: Complete the ray tracings for a converging lens for the following five situations (a through e) by drawing the three principal rays:

*Converging Lens Ray Tracings*

1. Straight through the middle.
2. Parallel $\rightarrow$ through the far $f$.
3. Through the near $f$ $\rightarrow$ parallel.

Identify in each situation where the image will form (if one exists).
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(a) Far away from $f$

(b) Near $f$

(c) On $f$
1.2: Which of the situations from 1.1 created a real image? Which situations created a virtual image? Which situations created no image?

1.3: Which of the situations from 1.1 created a magnified image? Which situations created a diminished image? Which are about the same size?

1.4: Which of the situations from 1.1 created an erect image? Which situations created an upside-down image?

1.5: Complete the ray tracings for a diverging lens for the following five situations (a through e) by drawing the three principal rays:

*Diverging Lens Ray Tracings*
1. Straight through the middle.
2. Parallel → away from the near f.
3. Toward the far f → parallel.

Identify in each situation where the image will form (if one exists).
Lenses

(a) Far away from $f$

(b) Near $f$

(c) On $f$
Lenses

1.6: Which of the situations from 1.5 created a real image? Which situations created a virtual image? Which situations created no image?

1.7: Which of the situations from 1.5 created a magnified image? Which situations created a diminished image? Which are about the same size?

1.8: Which of the situations from 1.5 created an erect image? Which situations created an upside-down image?
2. Working with a Single Converging Lens

2.1: Open Simulation 1, “lensesmirrors.air”, from your course materials webpage. Your screen should look like the one shown below:

![Simulation Image]

2.2: Drag the converging lens onto the ray optics area. Using the on-screen ruler measure the focal length of the lens.

![Ray Diagram Image]

*Figure 1 - In the image above is a ray diagram representation of the Optical Experiment taking place on the bench apparatus. The image screen can be moved by adjusting this gray circle – as illustrated by the mouse pointer.*
2.3: Drag the object to 12 cm away from the lens. Now slide the screen closer toward the lens. Stop when the image on the screen is in focus, and record in a table the object distance, image distance, the size of the image, and whether the image was inverted.

2.4: Calculate the magnification of the image (you will have to measure the size of the object to do so). Use the grid to help you – each square on the grid represents 1.0 cm. Add another column to your table for the magnification.

2.5: This simulation has a total of 5 convex lenses, each with a unique focal length, which you can cycle through using the box labeled “Mirror/Lens Number.” Repeat steps 2.2-2.5, using lenses 2-5. Is there any relationship you can see between the object distances in your table? The image distances?

2.6: Is there any relationship you can see between the magnifications in your table? Do the magnifications have the same sign? Are the images bigger than the object or smaller than the object?
3. Real Images of Images

3.1: Open Simulation 2 from your course materials webpage. Open the file “Real_Images_Of_Images.json”. Your screen should look like the one shown below. We will use a point source for the light source. There are two gray lines with red arrows at each end, both representing converging lenses (which we will refer to lens 1 and lens 2, respectively). The brown line between the two lenses will act as a screen.

3.2: Using the thin lens equation, calculate image distance from lens 1 to where the image will form. Place the screen at this location.

3.3: Calculate the magnification of this image using the magnification equation. Measure both the object and image heights to verify that this magnification calculation is indeed correct. Note that this simulation does not provide nice images like the ones in Simulation 1. You will have to imagine that the light rays are forming something interesting to look at.

If you want, adding a second point source in the same vertical, can help you visualize the magnification. Ask your TA if you don’t understand what I mean.
3.4: Remove the screen, but record where the screen was for easy reference.

3.5: Between the lens and the place where the screen was, are the light rays converging or diverging? What do you see when you look towards the light source in that region?

3.6: Even though the rays form an image on a screen, they keep on going straight once the screen is removed. It is as if there is a light source where the screen used to be that produces light, i.e. a new “object”. In the later parts of this lab section, consider only the region on the track further away than the screen used to be. You are going to attempt to create a new “image” from this new “object” using the +200 mm focal length lens (lens 2).

3.7: Using your knowledge of lenses as well as the focal length of lens 2, where can you put lens 2 to form another real image? Should you put lens 2 close to where the screen was, or far away? Experiment until you can form another real image of lens 2 that you can display on the screen. (Note: depending on where you place lens 2, the image may be off the end of the track) Record where you placed lens 2 and the screen.

3.8: What is the “object distance” for this second image (i.e. what is the distance from the new “object” to lens 2)?

3.9: What is the “image distance” for this second image (i.e. what is the distance from lens 2 to the new “image”)?

3.10: Measure the size of this second image. What is the total magnification of the whole system? What about just the magnification of just the lens 2 section? Do you think the original image from lens 1 still there?
Pre-Lab Assignment (1 point)

For each of the five ray tracing diagrams pictured below, identify whether the lens is a (a) converging lens, (b) diverging lens, or (c) the rays are drawn incorrectly.

1.

2.

3.
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4.

5.