Lenses

Goals and Introduction

When a ray of light strikes the surface of a material, some of the light may be reflected and some transmitted into the material. The portion of the light ray that is transmitted into the material undergoes refraction, based on the difference between the index of refraction of the material and the incident medium. This refraction, or bending of the light ray will occur again when that light ray exits the material and transmits back into the surrounding medium. The refraction of the light ray at each boundary is governed by Snell's Law, as you may have investigated in the Reflection and Refraction of Light lab activity.

If the material is in the shape of a rectangular block, then a light ray that strikes the side is likely to exit the opposite side, traveling parallel to the original incident ray of light, but offset by a certain amount that would depend on the index of refraction of the material and the size of block. This is because the entrance and exit boundary surfaces are parallel to each other. This is itself an interesting, measurable phenomenon, but of further interest is what happens when we change the shape of the entrance and exit surfaces of the material.

If we curve the entrance and/or exit surfaces of the material so that they have a spherical shape, we will find that applying Snell's Law at each boundary results in light undergoing a net refraction either towards, or away from a line that passes through the center of the material. We call this line the *principal axis*. If the shape of the lens results in the light being bent towards the principal axis, we call this type a lens a *converging lens*. If the shape of the lens results in the light being bent away from the principal axis, we call this type a lens a *diverging lens*.

Figure 1 illustrates what happens to light rays that are parallel (from a very distant source) when they are *focused*, or refracted by a converging lens. This kind of diagram is called a ray diagram. We see that the rays cross the principal axis at a single point, called the *focal point* of the lens. The distance from the center of the lens to this point is called the *focal length* of the lens. The focal point is the place where an image, created by the lens, would form if the object, or source, is very far away from the lens (thus, making the incident light rays nearly parallel).

Figure 2 illustrates what happens to light rays that are parallel (from a very distant source) when they are refracted by a diverging lens. In this ray diagram, we see that the light rays emerge as if they all had passed through a *focal point* that is behind the lens on the incident side. The distance from the center of the lens to this point is called the *focal length* of the lens. The focal point is the place where an image would appear to have been created if we look through the lens towards the object. The light our eye would collect would look like it was coming from the focal point!

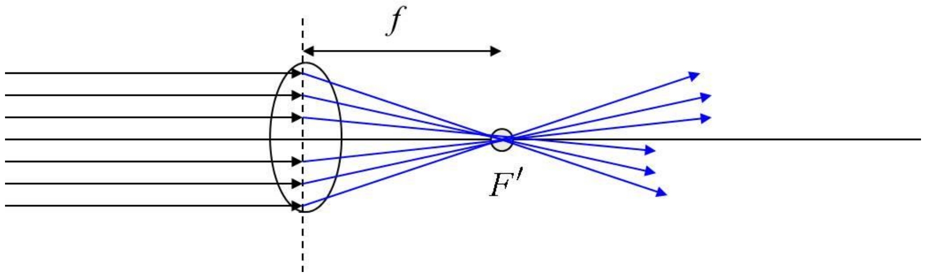

Figure 1

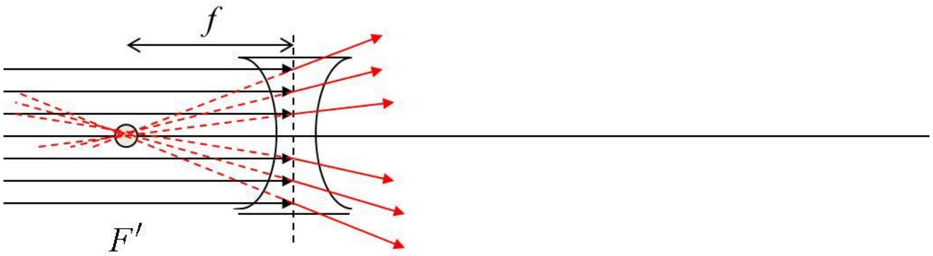

Figure 2

The behavior of incident light that is parallel to the principal axis through the center of the lens is established in the above ray diagrams, but what if the rays are coming from an object, or source, much nearer the lens? If we imagine light rays leaving in different directions from a single point on the object, it is clear they will not hit the lens traveling parallel to the principal axis, as was the case in Figure 1 and 2. What we would like is to identify a set of predictive behaviors for some of these rays, so that we can still locate where the emerging rays cross, or where they appear to cross, when viewed by an observer to the right of the lens (we always draw our ray diagrams with the light traveling from left to right).

To aid in developing rules for some rays and how they will behave when passing through the lens, we define a focal point on each side of the lens, where each is a focal length from the center of the lens. For the purposes of trying to create a self-consistent set of rules, we place a "prime" symbol on the right focal point for the converging lens and a "prime" symbol on the left focal point for the diverging lens. The following can then be stated for the drawing of three rays, originating from the same point on the object, which will aid in locating the image (where the emerging rays cross, or appear to cross):

> The ray leaving a point on the object parallel to the principal axis is deflected so that it passes through the focal point, *F'* of the lens (or travels in a direction as if it traveled through the focal point *F'*).

The ray that goes through the focal point, *F*, or travels in an incident direction as if it were going through the focal point *F*, emerges from the lens parallel to the principal axis.

The ray directed at the center of the lens is undeflected.

We can see an example of these rules applied to light leaving the top of an object with its bottom in line with the principal axis (Figure 3). This allows us to locate the image because light leaving the bottom of the image would emerge along the principal axis, meaning the bottom of the image will be located on the principal axis also.

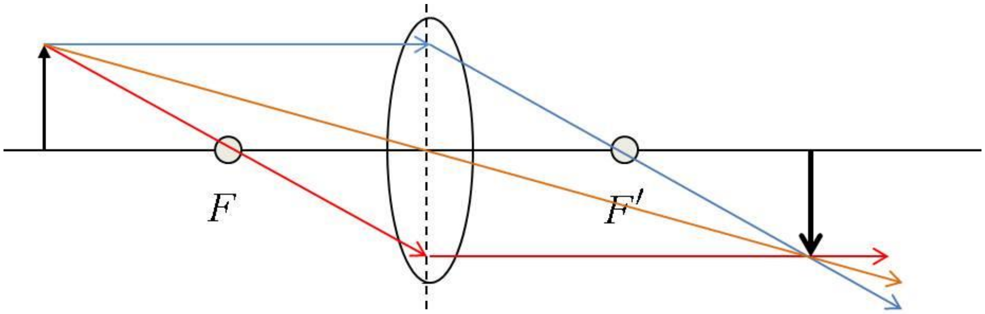

Figure 3

We can also draw these rays, following the same rules for the diverging lens (Figure 4). Note that the "primed" focal point is on the left for the case of the diverging lens, which means we interpret the rules in a somewhat strange way. The incident ray that travels parallel to the principal axis should emerge through *F'*, or along a direction as if it went through *F'*. We had to *back-trace* the ray from the vertical line of action through the lens (where we can imagine that net refraction occurs – it of course really occurs at the entrance and exit surfaces) until it hit *F'* and then extend the line forward. A similar thought process must be applied to the incident ray that travels "as if it were going to go through the focal point *F*" in order to choose the proper initial direction before it emerges parallel to the principal axis. Also, note that because the light

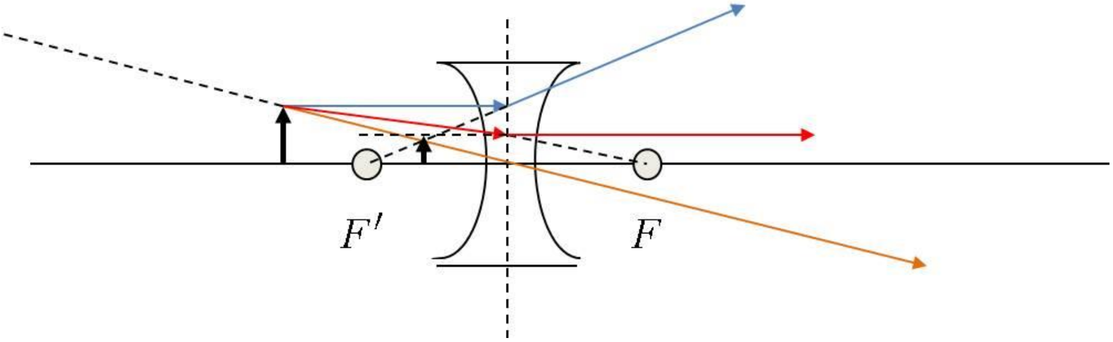

Figure 4

travels away from the principal axis after passing through a diverging lens, there is no possible way for it to cross on the right side of the lens. In order to find the image, we must back-trace each of the emerging rays to see where they appear to cross behind the lens.

When the emerging rays actually cross on the right side of the lens, we say this is a *real image* because the light is actually focused there and is present at that location. This means the image could be projected onto a screen. When the light appears to cross on the left side of the lens (such as in the case of a diverging lens), we say this is a *virtual image*, and can only be seen by looking back through the lens and seeing where the light appears to be coming from. If you were to place a screen there, you would not be able to get an image to appear on the screen because the light is not actually passing through that location – it just appears to be coming from there. There is an interesting scenario where a converging lens can be used to produce a virtual image, instead of a real image. Do some research to understand how this could be possible!

Now, in either case, we define the distance of the object from the center of the lens as s_o and the distance of the image from the center of the lens as s_i (Figure 5). Recall that the focal length of the lens is the distance between a focal point and the center of a lens, f. We can also define the height of the object as h_o and the height of the image as h_i. Realize that, for each of these quantities, there is a sign convention, as defined in your textbook. For example, the focal length of a converging lens is quoted as a positive value, whereas the focal length of a diverging lens is quoted as a negative value. Please consult your textbook to become familiar with the sign conventions for the other quantities, as this will be necessary to answer pre-lab questions in addition to performing calculations in this lab activity.

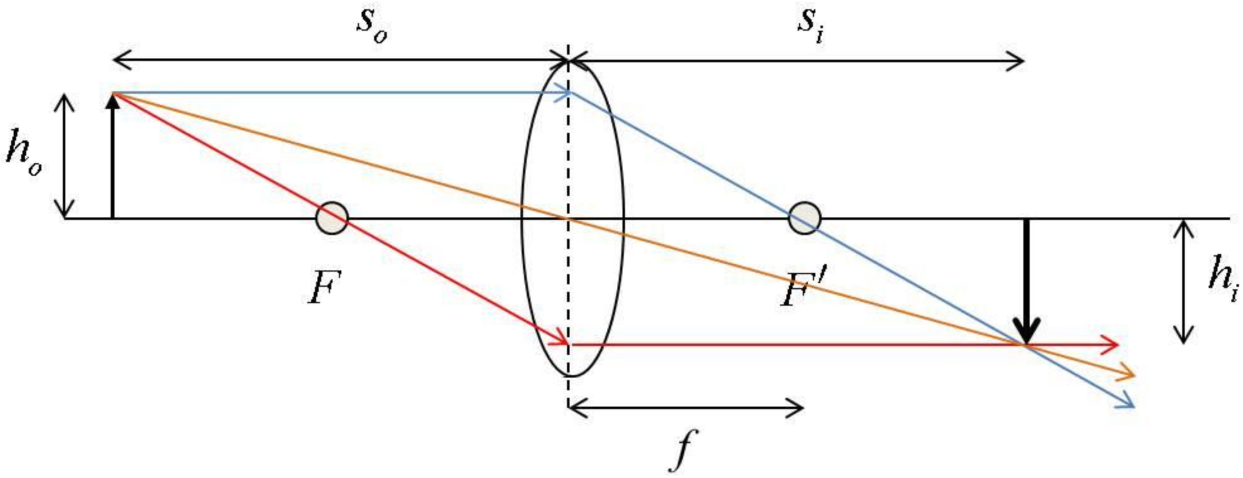

Figure 5

There are two primary relationships between these quantities that apply to either lens when lgith passes through them – Eq. 1 and Eq. 2. Remember that there are sign conventions for each of these quantities that must be followed. The first equation is called the *thin lens equation*, since it applies well when the lens material is thin. The second equation defines the magnification of the image, m, which can be expressed in terms of a ratio of the image and object height, or in terms of the negative ratio of the image distance and object distance.

$$\frac{1}{s_o}+\frac{1}{s_i}=\frac{1}{f} \qquad \text{(Eq. 1)}$$

$$m=\frac{h_i}{h_o}=-\frac{s_i}{s_o} \qquad \text{(Eq. 2)}$$

Lastly, it is possible to model the behavior of light as it passes through one lens and then a second lens. Realize that the light that will enter the second lens in the series is what has emerged from the first lens. This means that the second lens doesn't "see" the original object, but "sees' the image from the first lens. This means that the object distance for the second lens is the distance between the image location from the first lens and the center of the second lens! Also, the height of the image from the first lens will be the object height for the second lens! The thin lens equation and the magnification can then be applied for the second lens to find the final image location and height.

In today's lab, you will investigate the focal length of a converging lens and confirm the thin lens equation by projecting an image on the screen. You will also investigate the criteria required for the converging lens to create a virtual image, instead of a real image. Finally, you will attempt to confirm the focal length of a diverging lens by using a multi-lens system.

Goals: (1) Explore and investigate the properties of converging and diverging lenses
(2) Measure and confirm the thin lens model
(3) Utilize and solve a multi-lens system for the purposes of determining the focal length of a diverging lens

Procedure

Equipment – mini-optics bench, light source, crossed-arrow object mask, three component carriers, 75 mm convex lens, 150 mm concave lens, screen, a window

NOTE: The room lights should be turned down during the rest of the experiment.

1) Lay out the lab optics bench from the kit box. Note that the rulers on the sides are in units of mm. You can place components of this lab on this bench during the experiment. Some are magnetic and will be held in place when you place them on the bench.

2) Place the 75 mm convex lens on a component carrier and then place the carrier on the bench. Place the screen on a carrier and then place that carrier on the bench, as well.

NOTE: The word "convex" here refers to the shape of the entrance and exit surfaces of the lens. This results in a converging lens, so remember that the 75 mm convex lens is a converging lens!

3) **Record** the expected focal length of this converging lens, 75 mm.

4) Go to a window, or in the hall so that you can have light from a very distant object pass through the lens, and then strike the screen. Move the screen, or the lens, until you are able to create a focused image of the object on the screen. **Measure and Record** the distance between the lens and the screen, which is the experimental focal length of the lens.

Question 1: Why should the distance you just measured be representative of the focal length of the lens? Consider Figure 1 in your explanation. Is this image inverted or is does it have the same orientation as the object? Explain this observation.

5) At your table, place the light source on the optics bench at one end. Place the crossed-arrow object mask onto a component carrier. Then place that carrier in front of the light source, up against the source. Place the lens carrier after that and finally the screen carrier.

6) **Measure and record** the height of the vertical arrow on the crossed-arrow object mask. This will be the initial object height during the experiment.

7) Note the position of the crossed-arrow object mask along the optics bench. Move the lens so that the distance between the object and the lens is about 10.0 cm. **Measure and record** the object distance you have and then move the screen to locate what you feel is the location where the image is in focus. **Measure and record** the image distance, the distance between the lens and the screen. **Measure and record** the height of the image on the screen. You may want to apply any sign conventions for these quantities, if necessary.

8) Repeat step 7 using approximate object distances of 15.0 cm, 20.0 cm, and 25.0 cm. Then, **construct** a single ray diagram, for the converging lens in one of these scenarios.

9) Now, move the lens so that it is 6.0 cm from the crossed-arrow object. Note that you are not able to find a real image on the screen. Look through the lens from the side where the screen was located. You will likely see the object still, because your eyes collect from behind the lens, but you should also see a virtual image of the object within the lens. **Record** your observations about this image – is it magnified? Right-side up or upside down? Is it closer to the lens than the object or further away?

Question 2: Why was a virtual image formed with the object at that distance from the lens?

10) Place the 150 mm concave lens on a component carrier and place it between the crossed-arrow mask carrier and the 75 mm lens carrier on the optics bench. **Record** the expected focal length of the diverging lens, -150 mm.

NOTE: The word "concave" here refers to the shape of the entrance and exit surfaces of the lens. This results in a diverging lens, so remember that the 150 mm concave lens is a diverging lens!

11) Place the 150 mm lens about 4.0 cm after the crossed-arrow object, and then place the 75 mm lens about 6.0 cm after the 150 mm lens. Finally, place the screen after the 75 mm lens and locate a focused image by moving the screen back and forth. **Measure and record** the distance between the crossed-arrow object and the 150 mm lens (the first lens), the distance between the lenses, and the distance between the 75 mm lens (the second lens) and the location of the image. Note that the first value is the object distance for the first lens, and the last value is the image distance for the second lens. Also, **measure and record** the height of the image on the screen. This value is the image height for the second lens. You may want to apply any sign conventions for these quantities, if necessary.

12) Try moving the second lens and the screen to find another set of distances where a focused image forms on the screen. Repeat the measurements of step 11 once you have created this setup.

13) Try to **construct** a single ray diagram, for the multi-lens system with the diverging lens first and the converging lens second.

Question 3: Why can't we repeat the procedure we used at the start of the lab to find the focal length of the diverging lens? Explain your answer.

Question 4: Could we repeat the procedure in step 11 or 12 with the lenses reversed? Why or why not? In other words, is there a scenario where we could get an image to appear on the screen if the lenses are reversed? Feel free to try this, but either way, explain why, or why not, this is possible.

As always, be sure to organize your data records for presentation in your lab report, using tables and labels where appropriate.

Data Analysis

Use the data from steps 7 and 8 to calculate the focal length of the converging lens. Then, calculate the mean value of your results.

Use the data from steps 7 and 8 to calculate the magnification and image height in each case without using the image height you measured experimentally.

For the multi-lens system in step 11, use the thin lens equation for each lens, the data you gathered, and the expected focal length of the converging lens to calculate the focal length of the diverging lens. Be careful with all of your sing conventions!

For the multi-lens system in step 12, use the thin lens equation for each lens, the data you gathered, and the expected focal length of the converging lens to calculate the focal length of the diverging lens. Be careful with all of your sing conventions!

Calculate the mean value for the focal length of the diverging lens.

Error Analysis

Calculate the percent error between the focal length you measured in step 4 and the expected focal length of the converging lens.

$$\%error = \frac{\left| f_{\text{experimental}} - f_{\text{expected}} \right|}{f_{\text{expected}}} \times 100\%$$

Calculate the percent error between the mean value of the focal length of the converging lens you found in the Data Analysis section and the expected focal length of the converging lens.

For each case in steps 7 and 8, calculate the percent error between each of the image height that you measured and the image height you calculated in the Data Analysis section.

$$\%error = \frac{\left|h_{\text{measured}} - h_{\text{data analysis}}\right|}{h_{\text{data analysis}}} \times 100\%$$

Calculate the percent error between the mean value of the focal length of the diverging lens you found in the Data Analysis section and the expected focal length of the diverging lens.

$$\%error = \frac{\left|f_{\text{experimental}} - f_{\text{expected}}\right|}{f_{\text{expected}}} \times 100\%$$

Question 5: Is the thin lens equation accurate, as stated? What sources of error might be responsible for deviations from this model? Explain your answer by referencing your results.

Questions and Conclusions

Be sure to address Questions 1 through 5 and describe what has been verified and tested by this experiment. What are the likely sources of error? Where might the physics principles investigated in this lab manifest in everyday life, or in a job setting?

Pre-Lab Questions

Please read through all the instructions for this experiment to acquaint yourself with the experimental setup and procedures, and develop any questions you may want to discuss with your lab partner or TA before you begin. Then answer the following questions and type your answers into the Canvas quiz tool for “Lenses,” and submit it before the start of your lab section on the day this experiment is to be run.

PL-1) When an image appears on a screen, we can assuredly say that the image is

A) a virtual image.

B) a real image.

C) upside down.

D) right-side up.

PL-2) An object is placed 10.0 cm in front of a converging lens with a focal length of 5.0 cm. What is the image distance? Express your answer in cm.

PL-3) An object is placed 10.0 cm in front of a diverging lens with a focal length of -5.0 cm. What is the image distance? Express your answer in cm.

PL-4) When an object is placed in front of a diverging lens, the image is formed on the left side of the lens (the same side as the object), and the image distance is negative. Suppose you have light from an object pass through a diverging lens and then a converging lens that is 10.0 cm away from the diverging lens. When writing the thin lens equation for the second lens (the converging lens), the object distance is

A) less than 10.0 cm.

B) equal to 10.0 cm

C) greater than 10.0 cm.

D) 0 because the light doesn’t get there.

PL-5) A diverging lens with focal length -15.0 cm has an object placed 5.0 cm in front of it. A converging lens with a focal length of 8.0 cm is placed on the other side of the diverging lens, 10.0 cm away. How far from the converging lens will the final image be located? In other words, find the image distance for the converging lens. Express your answer in cm.