

## 1 Objective

- To explore the use of lenses to make images.

## 2 Introduction

A lens is an optical device used to form images or manipulate light. It can be thought of as two refracting surfaces in series. For refracting surfaces, the relationship between the object and image distances is given by the refracting surface equation:

$$\frac{n_1}{p} + \frac{n_2}{q} = \frac{n_2 - n_1}{R} \quad (1)$$

where  $n_1$  is the refractive index of the material the light comes from,  $n_2$  is the refractive index of the material the light travels into, and  $R$  is the radius of curvature of the surface. ( $R \rightarrow \infty$  for a flat surface.) If light rays are parallel approaching a boundary, this is an infinite object distance,  $p \rightarrow \infty$ .

This equation can be used twice to find how far from the back surface of the lens the image will appear. In that case, the object for the second surface is the image created by the first surface, and the object distance for the second surface  $p_2 = -q_1 + t$ , where  $t$  is the lens thickness. If the lens thickness is very small compared to the object and image distances, the two equations taken together become:

$$\frac{1}{p} + \frac{1}{q} = (n - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) \quad (2)$$

where we assume the lens has refractive index  $n$  and is surrounded by air. Since by definition the focal length  $f$  is the distance from the center of a lens to where an image forms when the object is at infinity, taking  $p \rightarrow \infty$  and  $q = f$  we can see that

$$\frac{1}{f} = (n - 1) \left( \frac{1}{R_1} - \frac{1}{R_2} \right) \quad (3)$$

and equation (2) can be written

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad (4)$$

where  $p$ ,  $q$ , and  $f$  are all measured from the center of the lens.

A lens can create an image that magnifies or reduces the object. The magnification of the object is given by

$$M = -\frac{q}{p} \quad (5)$$

so that the size of the image is  $M$  times the size of the object and if  $M$  is negative that indicates the image is inverted (upside down).

This lab will be done virtually using two *PhET* simulations created at the University of Colorado at Boulder. Click [here](#) to get started with the Geometric Optics simulation and [here](#) for the Bending Light simulation.

## 3 Procedure

### 3.1 Behavior of a Converging Lens

1. Open the Geometric Optics simulation.
2. You will see the an object (the pencil), a double convex lens, and a horizontal guide line through the center of the lens (the principle axis). On the principle axis the focal points of the lens are shown with  $\times$  marks.

3. Move the pencil object to the focal point and confirm that the rays emerge from the lens parallel. What is the image distance in this case?
4. Move the object closer to the lens. What happens to the image? Check the *Virtual Image* box to show the virtual image. This is what you would see if you looked into the lens from the right hand side. (A virtual image cannot be projected onto a screen. You can confirm this by checking the *Screen* box and moving the screen around. Untick the *Screen* box.)
5. You can change the refractive index,  $n$ , and curvature radius of the lens,  $R$ . Choose any values you like, so long as the focal length is between about 40 and 110 cm. Tick the *Ruler* box to make sure your values give a focal length in this range. Record  $n$  and  $R$  and then keep them constant for the rest of the lab.
6. Move the object so its object distance is less than  $f$ , then between  $f$  and  $2f$ , then greater than  $2f$ . Complete Table 1

$p$ is	$ q  \stackrel{?}{\leq} p$	image real or virtual?	image inverted or upright?	$ M  \stackrel{?}{\leq} 1$
$p < f$				
$f < p < 2f$				
$p > 2f$				

Table 1: Table for section 3.1.

### 3.2 Determining Focal Length

1. Tick the *Ruler* box. Measure the object distance  $p$  and, without moving the object, measure the image distance  $q$ . For a virtual image, record  $q$  as negative. Record these points in a table and their inverses (see Table 2).
2. Repeat so that you have 8 pairs of values for  $p$  and  $q$ . Make sure to have some values of  $p$  that are greater than the focal distance and some that are less than the focal distance. You can move the lens if you need to.
3. Plot a graph of two of the columns in your table, one on the horizontal axis and one on the vertical, so that the result is a straight line. From the graph, extract a value for the focal length. Make sure to include your graph in your submission.
4. Now calculate the focal length using equation (3). Find the percentage error between these two values, taking the calculated value to be the theoretical one and the value from the graph to be the experimental one.

$p$ (cm)	$q$ (cm)	$\frac{1}{p}$ (cm <sup>-1</sup> )	$\frac{1}{q}$ (cm <sup>-1</sup> )

Table 2: Example data table for section 3.2. Your table will require more rows.

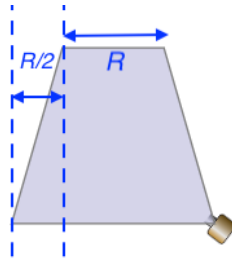


Figure 1: Dimensions of trapezoid prism.

### 3.3 Thick Lens

1. Open the Bending Light simulation and choose *Prisms*.
2. Switch on the light and choose the red ray (leave the wavelength at 650 nm).
3. Still on the *Prisms* screen, pull out a circle prism and put it precisely on axis with the source so the ray of light is bisecting the circle. To ensure that you have it exactly centered: check the *Normal* box to show the dashed normal incidence lines and make sure that the ray is going exactly along those lines at both the front and back on the circle.
4. Now uncheck the *Normal* box and switch to the source producing 5 parallel rays. Notice that the circle prism acts as a thick converging lens that focuses the rays to a point behind circle.
5. Let the radius of the circle be  $R$ . Using equation (1) *twice* find an expression for the image distance  $q_2$  from the back of the circle lens in terms of the refractive index of the prism pieces  $n$  and  $R$ . Remember that the object distance in this case is infinite.
6. Taking  $n = 4/3$  for water and  $n = 1.5$  for glass predict how far behind the back of the circle the rays will be focused in terms of  $R$  for water and for glass.
7. Choose *water* for the prism material. You can use the trapezoid prism to measure how far behind the back of the circle the rays are being converged in terms of  $R$ . Keep the trapezoid in its initial orientation (do not rotate it) and notice the length of the top side is  $R$  and the horizontal distance covered by each non-parallel side is  $R/2$  (see figure 1). You will have use the straight edges of several prism to align the trapezoid, without making the image, then move the extraneous prisms away and make the image with the trapezoid positioned alongside. Make a sketch or include a screenshot. Does your prediction match what you see in the simulation?
8. Repeat the previous step with the prism material set to *glass*.
9. Now use equation (3) to predict where the image would be. Remember that if the object is at infinity, the image should be at the focal point of the lens, with the image distance  $q$  measured from the center of the lens.
10. Does this calculation agree with what you see in the simulation? Should it? Why or why not?