Name ________________________ Date ____________ Time to Complete ____h ____m

Partner ________________________ Course/Section ______/_______ Grade __________

Geometric Optics

Introduction

With this experiment we begin the study of light and its interaction with various optical components. In this experiment we shall study the limit where the wave nature of light can be neglected and we can consider a train of light waves to be a straight line, or ray. Wave effects are usually unimportant when the size of the optical component is much larger than the wavelength of the light which is interacting with it.

1. Reflection and refraction

Introduction

The index of refraction of an optical medium is defined as the ratio of the speed of light in a vacuum, c, to the speed of light in the optical medium, v:

$$n = \frac{c}{v} \tag{1}$$

In general, the speed of light in an optical medium depends on the wavelength of the light. Therefore, the index of refraction will also depend on the wavelength. This dependence of index of refraction on wavelength, called dispersion, explains how a prism is able to spread a beam of white light into its component colors.

Figure 1 shows a light ray, in an optical medium having index of refraction n_1, incident from the right onto an interface separating the first optical medium from a second optical medium having index of refraction n_2.

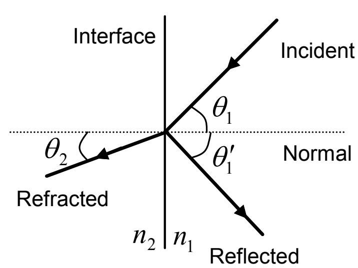


Figure 1: Reflection and refraction where $n_2 > n_1$

As the figure shows, an incident ray of light will, in general, split into two parts as it hits the surface separating the two media. One part, the reflected ray, will remain in the first medium, and will make an angle, measured relative to the normal to the surface, that equals the angle the incident ray made with the normal. Expressed mathematically, the Law of Reflection says:

$$\theta_1 = \theta_1' \tag{2}$$

The second part, the refracted, or transmitted, ray, proceeds on into the second medium. This ray makes an angle, θ_2 , measured relative to the normal line in the second medium, which is determined by the Law of Refraction, also known as Snell's Law. Snell's Law states that:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{3}$$

Figure 1 above represents a situation where $n_2 > n_1$, resulting in θ_2 being smaller than θ_1. If $n_2 < n_1$ the situation is reversed and θ_2 becomes greater than θ_1. This would be the case, for example, if a ray of light already in an optical medium such as glass or transparent plastic was exiting back into an optical medium such as air. *Figure 2* depicts this situation.

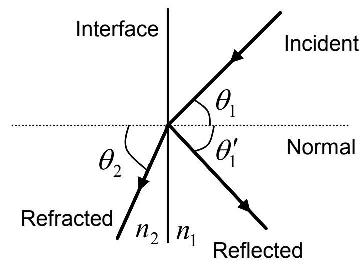


Figure 2: Reflection and refraction where $n_2 < n_1$

Note that this means as θ_1 increases, θ_2 will eventually approach 90°. But when $\theta_2 = 90^\circ$ it means that no refracted ray goes into the second medium. Rather, the incident ray is completely reflected back into the first medium. This phenomenon is called *total internal reflection*. Clearly this can happen only when a ray is incident from a medium of higher index of refraction into a medium of lower index of refraction. Referring to *Equation 3*, we see that total internal reflection first occurs when $\sin\theta_2 = 1$. When this happens, θ_1 is said to be at its critical value, θ_{crit}. This critical value of θ_1 can therefore be found by setting $\sin\theta_2 = 1$ in *Equation 3* and solving for $\sin\theta_1$. Remembering that θ_1 is now θ_{crit}, the resulting equation is:

$$\sin\theta_{crit} = \frac{n_2}{n_1} \tag{4}$$

a. Reflection at an $n_1 < n_2$ interface

Introduction

You will begin your investigations by testing the Law of Reflection expressed in *Equation 2*.

Procedure

- Attach the optical table to the optics bench and place the semicircular plastic lens on the optical table. The center of the flat face of the lens should be aligned with the line on the table labeled "component", and the normal line should intersect the center of the flat face as shown in *Figure 3*.
- Attach the light source to the optics bench and orient the light source so that a single ray of white light leaves the source and shines along the normal line on the optical table. The system should be aligned so that this incident ray (A) strikes the center of the flat face of the semicircular lens. The angle of incidence (θ_1) can then be varied by rotating the optical table. Note that the refracted ray (C) should not change direction as it exits the circular face of the lens.

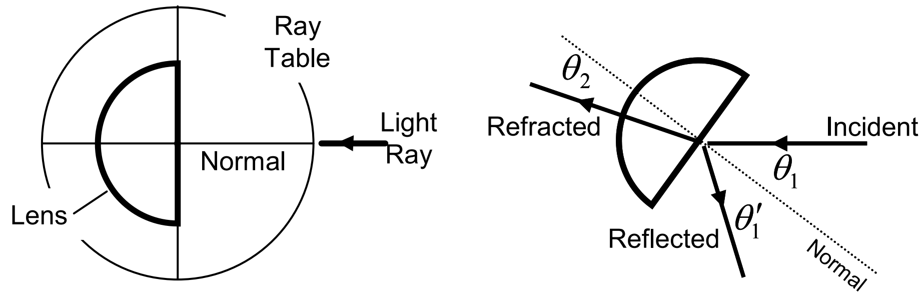


Figure 3: Apparatus alignment

Procedure (cont.)

- Now vary the angle of incidence from 10° to 80° in 10° increments. For each angle of incidence, measure and record the angles of incidence, reflection, and refraction in *Table 1*. (You will fill in the final three columns in the next section of the lab.)

Incident Angle θ_1	Reflected Angle θ_1'	Refracted Angle θ_2	Sin θ_1	Sin θ_2	Index of Refraction n

Table 1

Conclusion

Do you find that, within the uncertainty in your measurements (you should estimate this—are your measurements accurate within + or - 1° ?, 2° ?, or what?), the angle of *reflection* equals the angle of *incidence* as predicted by the Law of Reflection? If not, redo the experiment taking greater care in aligning the apparatus and measuring the angles.

Question

You should have noticed that the incident ray refracts (bends) as it enters the plastic at the flat interface. You might also have noticed that that the ray does not bend again as it passes from plastic back into air? Why doesn't the ray bend at this interface?

b. Refraction at an $n_1 < n_2$ interface

Introduction

In this section you will use Snell's Law, *Equation 3*, and your data from part **a**, to determine the index of refraction of the plastic from which your lens is made. Proceed as follows:

Procedure

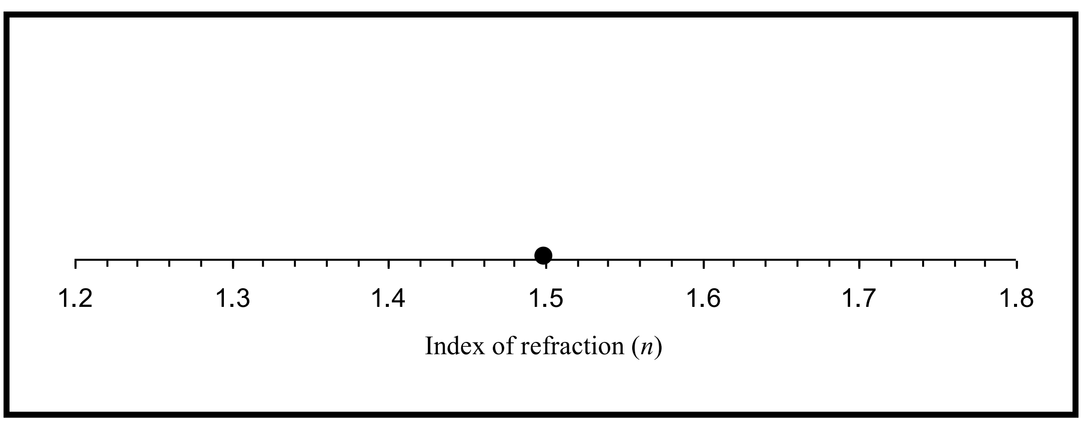
- For each angle of incidence, calculate sin θ_1 and sin θ_2 and record these values in *Table 1*.
- For each angle of incidence, use these values, and *Equation 3*, to calculate n_2. Assume that n_1, the index of refraction of air, is 1.00. Record these values in *Table 1*.
- Calculate and report the average and standard deviation of your results. The average of all your calculated values represents the most reliable value for your measurement of index of refraction, and the standard deviation is a measure of the uncertainty in your average value. (A simple measure of the standard deviation, the spread in your n values, is the difference between the largest and smallest values.)

Average n = ___________________

Standard Deviation of n = ±____________________
±½ (Max n – Min n)

Conclusion

According to the manufacturer, the index of refraction of the plastic from which the hemispherical lens is made is 1.50. Is there a significant discrepancy between your measured value and the manufacturer's value? (To visualize this, plot your best value on the number line below and include an error bar based on the standard deviation. If the manufacturer's value lies well outside the error bar, there is a significant discrepancy.) If yes, redo this portion of the experiment, taking greater care with your measurements.



c. Refraction at an $n_1 > n_2$ interface

Introduction

In this section you will test Snell's Law when light crosses an interface into a medium with a lower index of refraction.

Procedure

- Arrange the apparatus as shown in *Figure 4*. Note how the semicircular plastic lens has been rotated 180°.

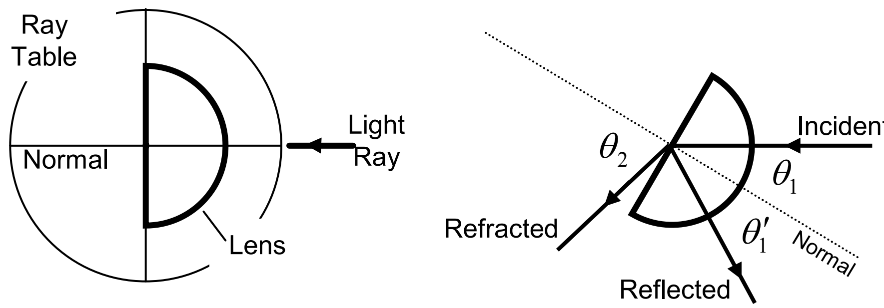


Figure 4: Apparatus Alignment

- Be certain that you arrange your apparatus so that the incident ray (A) undergoes no deviation at the cylindrical surface of the lens, and so that the incident ray inside the lens hits the flat surface at its center. You are now seeing refraction at the flat surface as the ray passes into a medium (air) having a lower index of refraction than the plastic, so the refracted ray (C) is bent away from the normal as it passes from the plastic into the air.
- Repeat the procedure of parts **a** and **b**, and make a second determination of the index of refraction of the plastic. Record your data in *Table 2*. Note that at some value of the angle of incidence, the refracted ray will disappear. Do not continue your measurements beyond this angle.

Incident Angle θ_1	Reflected Angle θ_1'	Refracted Angle θ_2	Sin θ_1	Sin θ_2	Index of Refraction n

Table 2

Average n = ___________________

Standard Deviation of n = ±___________________
±½ (Max n – Min n)

- Is there a significant discrepancy between your two measurements? To compare your two experimentally determined values of n plot this result with error bar on the number line at the bottom of page 4. If the error bars of your two measurements do not overlap then there is a significant discrepancy. If there is a significant discrepancy, repeat the procedure, taking greater care with your measurements.

- The value of the angle of incidence where the refracted ray disappears is the critical angle. Make three careful measurements of this angle and record your results in *Table 3*. (Attempt to make the three trials independent of one another. After completing the first measurement, return the incident angle to zero, and have a different person repeat the measurement without your assistance. Then repeat the measurement yourself.)

Trial	Critical Angle	n
1		
2		
3		

Table 3

- Use *Equation 4* to calculate the index of refraction of the plastic from your angle measurements. Compute the average n and its standard deviation. Is there a significant discrepancy between this result and your two previous results? To compare this result to your previous results add it, with error bar, to the number line at the bottom of page 4. If there is a significant discrepancy, repeat the procedure, taking greater care with your measurements.

  Average n = ______________________

  Standard Deviation of n = ±___________________
  ±½ (Max n – Min n)

d. Dispersion

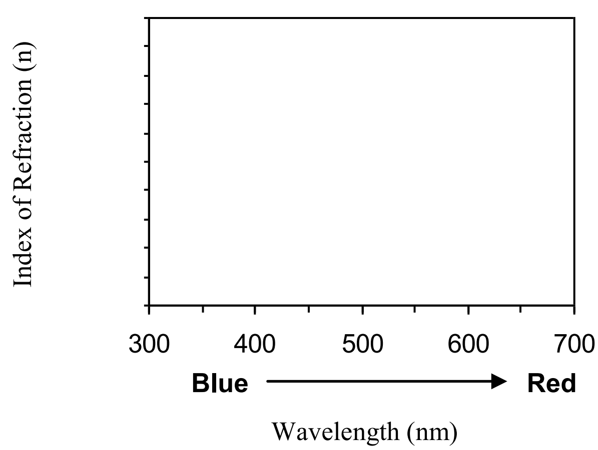
Questions

1. As you conducted your measurements in the previous two sections you should have observed clear evidence that the index of refraction for plastic is not a single number but actually is a function of the color of light. (This phenomenon is called dispersion.) Describe the evidence that suggests this conclusion.

2. What color light travels fastest in plastic? What color travels slowest? Describe the observations and the reasoning that led to this conclusion.

3. Determine the index of refraction at the two extremes of the visible spectrum. Add an appropriate vertical scale to the graph below and plot these two data points. Although the *shape* of the function is not known to us, with a freehand flourish pencil in the trend (upward or downward) on the graph. (Rhetorical: What atomic or molecular scale properties of a material cause the index of refraction to depend on wavelength?)

   Measurements and calculations:



2. Image formation by lenses

Introduction

From the point of view of optics, an *object* is a source of light rays. These rays may exist because the object itself emits them (such as, for example, light bulbs, stars, or the sun) or because the object reflects light from a source other than itself. Most objects (for example people, trees, rocks, *etc*.) fall into this second category. In either case, under certain conditions, a lens can form an *image* from the light rays coming from the object. The lens bends, or refracts, the light rays, causing them to interact in such a way as to form the image of the object from which they came. Careful measurements of the distance between the object and the lens (the *object distance, (p)*) and the distance between the lens and the image (the *image distance, (i)*) can be used to determine the *focal length, (f)* of the lens.

A simple way to understand how a lens works is to follow a procedure called *ray tracing*. A ray is an imaginary straight line that traces the path of the light. By following the paths of two or three specially selected rays coming from the same point on the object, it is possible to construct a diagram which visually depicts the creation of the *image point* of that point on the object. As they pass through the lens, the rays will be refracted at both the front and rear surfaces of the lens. After passing through the lens, the rays will, in general, intersect at some point in space, as shown in the example ray diagram in *Figure 5*.

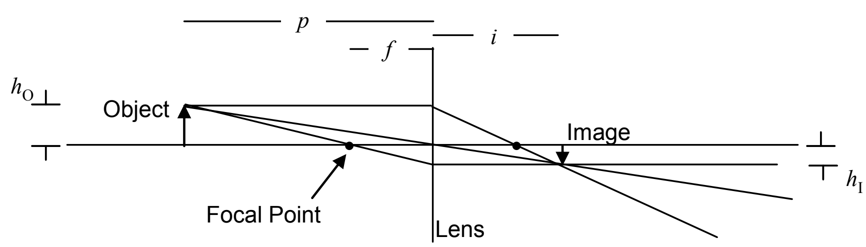


Figure 5: Example of ray tracing

This point is the image point we are looking for. If the lens is not too thick, it is possible to simplify the ray tracing process by assuming that the ray changes direction not at the surfaces of the lens, but rather at a plane through the middle of the lens. If the lens is sufficiently thin (such as the lenses we will be using in the lab), this approximation does not introduce any significant errors.

Your textbook gives a discussion of ray tracing, along with several examples. You might want to refer to this information as you work through this section.

For thin lenses, object distance p, image distance i, and focal length f, are related by a simple equation:

$$\frac{1}{p}+\frac{1}{i}=\frac{1}{f} \tag{5}$$

The ratio of the height of the image, h_I, to the height of the object, h_O, is called the *transverse magnification*, m. It can be calculated from:

$$\frac{h_I}{h_O}=m=\frac{-i}{p} \tag{6}$$

You will now determine the focal length of a positive lens by two different methods. Then you will use the measured focal length to predict the position the image distance in a variety of scenarios.

a. Measuring the focal length of a convex lens – Method 1

Introduction

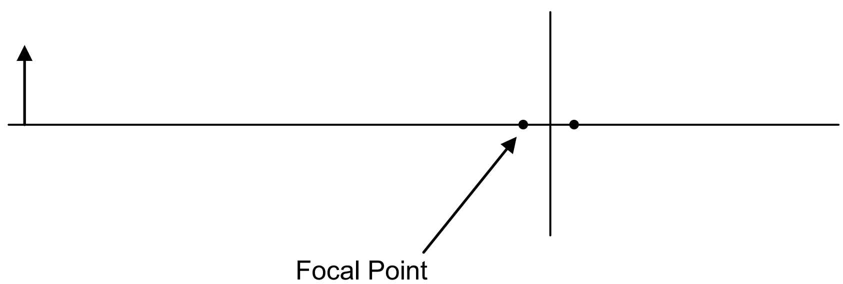
If the object is far from the lens, the value of $1/p$ becomes so small that $1/i$ approximately equals $1/f$. Or, in other words, i approximately equals f. The image produced will, in general, be quite small and will be located approximately at the focal point of the lens. This gives a quick way to make an approximate measurement of the focal length. Just position an object far from the lens and find where the image appears. You will do that here.

Procedure

- Remove the light source table from the optics bench and mount the lens and viewscreen on the optics bench.
- Orient the bench so that the image of a distant object, a lightbulb at the far end of the lab, for example, appears on the screen.
- Adjust the location of the screen until the image is sharp and clear. Measure and record the distance between the lens and the screen. This image distance approximately equals the lens's focal length.

  Approximate focal length = ________________

- Complete the ray diagram below depicting how this image is formed on the screen. Use a ruler. (Notice how the object distance is much greater than the focal length, just as it was in the actual experiment.)



b. Measuring the focal length of a convex lens – Method 2

Introduction

When the object distance is twice the focal length of the lens, *Equation 5* can be solved to show that the image distance is also twice the focal length. The transverse magnification is then -1. This means that the image is the same size as the object, but is inverted.

Procedure

- Use *Equation 5* to show that if $p = 2f$ then $i = 2f$ also.

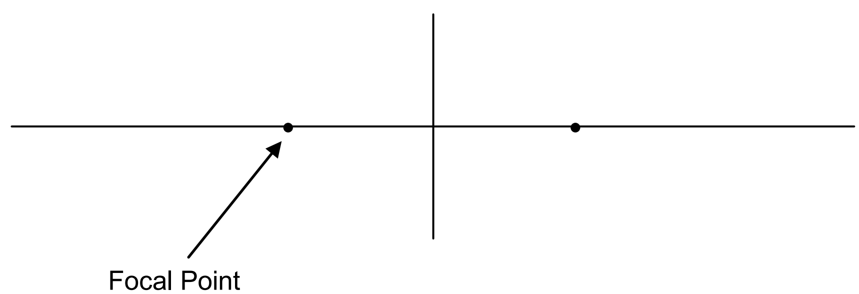
- Now mount the light source near one end of the optical bench and orient the source so that the face with the crossed arrows on it points toward the lens. Using your approximate focal length from Method 1 as a guide, locate the screen approximately *4f* from the light source, and place the lens halfway between them.
- Carefully adjust the positions of the lens and the screen until you have a clear image that is exactly the same size as the object, and so that the object distance equals the image distance. You should use the Vernier caliper at your lab station to measure the size of the image and the size of the object. (This adjustment is the trickiest part, it will take some time. You will have to adjust the position of both the lens and the screen to meet three criteria, simultaneously. The object distance must equal the image distance, the object height must equal the image height, and the image must be clear.)
- Measure and record your values for object distance and image distance and use them to calculate the focal length of your lens.

Object distance = ___________________

Image distance = ___________________

Calculated focal length = __________________

- Draw an accurate ray diagram depicting how the image is formed in this case. Use a ruler.



c. Predicting the image distance

Introduction

For an arbitrarily chosen object distance, and a lens of known focal length, *Equation 5* can be used to predict the location of the image. Your results from Method 2 should give you an accurate and reliable value for the focal length of your lens. There are three possible ranges in which the object distance can fall: $p > 2f$, $f < p < 2f$, and $p < f$. For each of these ranges, do the following:

Procedure

- Choose an object distance and use *Equation 5* to calculate a predicted value for the corresponding image distance.
- Setup your optics bench using your chosen value of object distance and your calculated value of image distance and see whether you do indeed get an image at the predicted location. If necessary, adjust the position of the view screen until you find the sharpest image. Measure and record your experimental values of p and i and compare the predicted and experimental values of the image distance.
- Draw an accurate ray diagram depicting the formation of the image in each case.

Case 1: $p > 2f$

Object distance = __________________

Predicted image distance = __________________

Measured image distance = ____________________

Ray diagram:

<u>Case 2</u>: $f < p < 2f$

Object distance = ________________

Predicted image distance = ________________

Measured image distance = __________________
Ray diagram:

____

<u>Case 3</u>: $p < f$

Object distance = ________________

Predicted image distance = ________________

Measured image distance = __________________

Ray diagram:

____

Conclusion

Summarize your understanding of image formation by lenses by completing *Table 4* below. Under what circumstances is the image larger than the object? Smaller? Same size? Are there circumstances when no (real) image forms at all? What about relative image size and orientation?

Object Distance	Image Size (enlarged or diminished)	Image Orientation (upright or inverted)	Image (real or virtual)
$p > 2f$			
$f < p < 2f$			
$p < f$			
p = very large			

Table 4