

5. GEOMETRIC OPTICS

Readings: Hecht, Chapter 24

Introduction

In this lab you will measure the index of refraction of glass using Snell's Law, study the application of the laws of geometric optics to systems of thin lenses, and construct a simple telescope and microscope.

The theory for the index of refraction measurement and Snell's law is covered in Hecht, section 24.4. The laws of geometric optics applied to thin lens systems are covered in 24.6 and 24.7.

Snell's Law

The index of refraction n of a material is defined to be

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v} . \quad (1)$$

For air, n is very close to 1.

For a light beam passing from medium 1 to medium 2 as in Figure 1, Snell's law is

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 , \quad (2)$$

where n_1 and n_2 are the indices of refraction of the two materials, and θ_1 and θ_2 are the angles of the light ray from the perpendicular to the interface.

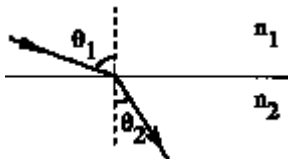


Figure1: A ray of light at an interface

Thin Lenses

The basic equation we will use is the thin lens equation:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f} , \quad (3)$$

where s is the distance from the object to the center of the lens, s' is the distance from the center of the lens to the image, and f is the focal length of the lens. An illustration for a converging lens is given in Figure 2.

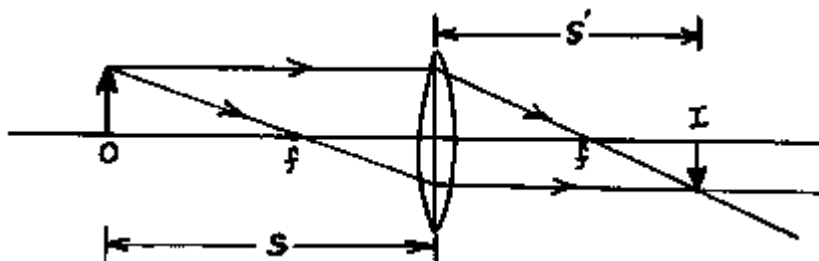


Figure 2: A converging lens with real image I and object O.

In this illustration, s , s' , and f are all positive. The sign convention is given in Hecht, p. 958. The rays converge at the image point s' . If we place a screen at s' , we will observe an image of the object. The image is thus said to be real (it can be seen on a screen). Note that the image is inverted.

The magnification is defined to be the ratio of the image height to the object height. If the image is inverted, then the magnification is negative. For a thin lens, the magnification M is given by

$$M = -\frac{s'}{s} . \quad (4)$$

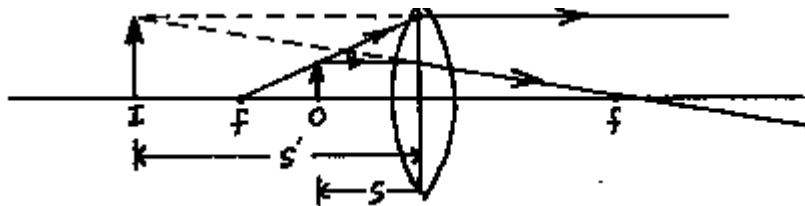


Figure 3: A converging lens with a virtual image.

An illustration of a virtual image is given in figure 3. In this example, s and f are positive, but s' is negative. The image appears as if it were at location s' . However, the light rays are not converging at s' . If we were to place a screen at s' , we would not observe an image of the object on the screen. The image is thus said to be virtual. Note that the image is erect.

The refractive power P of a lens is commonly given in diopters,

$$P = \frac{1}{f} , \quad (5)$$

where f is the focal length expressed in meters. Thus a lens with $P = 20$ has a focal length of $f = 1/20 \text{ m} = 0.05 \text{ m}$, or 5 cm. The power P is positive for a converging lens, and negative for a diverging lens. A typical prescription for a person who is mildly nearsighted would be a diverging lens with $P = -2$, or $f = -50\text{cm}$.

Combinations of Thin Lenses

Combinations of thin lenses can be handled by successive application of the thin lens equation to each of the lenses. A real image formed by one lens can serve as the object for another. See Section 24.6 in Hecht. We examine two useful lens combinations below.

The arrangement in figure 3 above corresponds to a simple magnifier. An object placed just inside the focal length of the converging lens gives rise to a magnified, *virtual* image. A similar principle is used in the compound microscope (Hecht, p. 974).

We first use a converging lens to form a *real*, inverted image, as in figure 2. This lens is called the objective, and typically has a short focal length. We then use a simple magnifier, called the eyepiece, to enlarge this image. The best results are obtained when the object is placed just outside the focal distance of the objective, and the image formed by the objective is just inside the focal distance of the eyepiece. This means that the distance between the two lenses is much greater than the sum of the two focal lengths. (Once you have your microscope built, notice whether it's really magnifying or not.) Do you have a real or inverted image? Which do you want?

The principles behind the refracting telescope are similar to those behind the compound microscope. However, the object is now assumed to be very far away, so light rays from the object are essentially parallel. The objective typically has a long focal length. The eyepiece is again used to magnify the image formed by the objective. The distance between the two lenses is approximately equal to the sum of the two focal lengths.

Experimental Procedure

Experiment 1: Snell's law

The configuration for determining the index of refraction of the glass is shown in Figure 4.

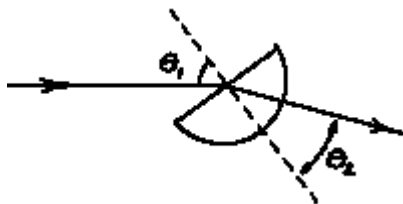


Figure 4: Determining n from Snell's law

The light is refracted upon entering the semicircle of glass. However, since the light exits the glass perpendicular to the interface, it is not refracted a second time. Thus, you need only consider refraction at the first interface.

- 1) For at least 3 different incident angles, determine the index of refraction of the glass from measurements of the angles of incidence and refraction of the laser beam. Take the average of your measurements as the best estimate of n .

- 2) Determine how to measure the angle of total internal reflection using this apparatus. Find out what the critical angle is using your design.

Experiment 2: The thin lens equation

For each of these experiments, be sure to draw the configuration of the lenses, light source, and screen in your notes. Record whether the image is real or virtual, and whether it is inverted or erect. *Measure the actual focal length of each of your lenses, as it may differ from the nominal value.*

- Single converging lens—Real Image.** Use either the $P = 10$ or $P = 20$ di lens. Place the object light source outside the focal length of the lens, as in Figure 2 above. Find the image point s' such that the image is focused on the screen. For at least 3 different object distances, determine s' and the magnification M . Compare your answers with the expected values.
- Single converging lens—Virtual Image.** Use the $P = 10$ di lens. Place the object light source inside the focal length of the lens, as in Figure 3 above. Find the location of the virtual image in the following way: Place the screen behind the light source. Look through the lens at the object and over the top of the lens at the vertical line on the screen. Move your head slightly from side to side. If the line and the object arrow appear to move relative to each other, then they are in different planes, and the apparent relative motion is due to parallax. Move the screen until the line on the screen and the object arrow do not move relative to each other as you move your head. The screen is now at the image point s' . Record s' and compare with the expected value. Estimate the apparent size of the virtual image and compute the magnification M . Compare with the expected value. This part of the lab is slightly difficult and tends to strain your eyes. Don't spend excessive amounts of time on it.

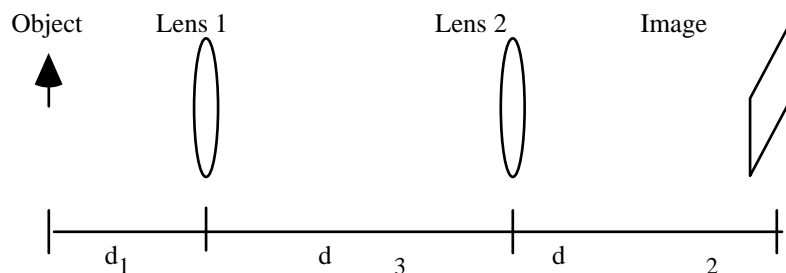


Figure 5: The arrangement and notation for parts 3 and 4

- Compound Systems.** Use the $P = 10$ and $P = 20$ di converging lenses to form a real erect image of the arrow. Make sure that the lenses are separated by a distance greater than the sum of their focal lengths.

Find the location of the image. Measure the distances from the object to the first lens, between the lenses, and the distance from the second lens to the image. Compare the image distance to the predicted value. Measure the magnification M of the image and compare to the predicted value.

- 4. Compound Systems—Diverging Lens.** Replace the $P = 20\text{di}$ lens by the $P = -6.67\text{di}$ diverging lens. Arrange the lenses such that you form a real, inverted image on the screen. Record all the distances. Compare the image distance to the predicted value. Measure the magnification of the image and compare to the predicted value.
- 5. Optional.** This method can also be used to determine the focal length of an unknown diverging lens. If you have eyeglasses, determine the focal length of your lenses.

Experiment 3: Optical instruments

- 1. Compound Microscope.** Build a compound microscope. Use the $P = 20\text{di}$ lens for the objective and the $P = 10\text{di}$ lens for the eyepiece. Note that these are the same lenses used in part 3, but that a different effect is achieved. You may find it easiest to first locate the image formed by the objective using the screen and then place the eyepiece such that it magnifies the image. Record the configuration that works best for you. Record whether the image is real or virtual, and whether it is erect or inverted. Try using the $P = 10\text{di}$ lens for the objective and the $P = 20\text{di}$ lens for the eyepiece. Again, adjust the positions to get the best image. What qualitative changes do you observe?
- 2. Refractor telescope.** Build a refractor telescope. Use the large $P = 2\text{di}$ lens for the objective and the $P = 20\text{di}$ lens for the eyepiece. Try your telescope on several distant objects out the window. Record the configuration that works best for you. Record whether the image is real or virtual, and whether it is erect or inverted. Read the sign hanging in the tree near the observatory using your telescope and record what it says in your notes. (*Do not speak this out loud unless you are the last group to read the sign!*)

Name: _____

Date: _____

Lab Partner: _____

Report Form: Geometric Optics

Experiment 1 (Snell's Law)

Give your average value of the index of refraction, n , including uncertainty: _____

Describe how you measured the critical angle, and show how you used it to calculate the index of refraction.

Does this value for index of refraction agree, within uncertainty, to your first calculated value of n ?

Experiment 2 (The thin lens equation)

In the table below, place your units in the parentheses provided.

s ()	s' ()	Focal length (mm)	Focal length calculated ()	M measured	M calculated
		100			
		100			
		100			
		100			

Average focal length of 10 di lens _____

s ()	s' ()	Focal length (mm)	Focal length calculated ()	M measured	M calculated
		50			
		50			
		50			
		50			

Average focal length of 20 di lens _____

Virtual Image: $P = 10$ di, $s =$ _____, $s' =$ _____

M calculated = _____ (from s and s')

M measured = _____

Report Form: Geometric Optics (cont.)

In the table below, refer to figure 5 for notation.

P_1 (di)	P_2 (di)	d_1 ()	d_3 ()	d_2 () calculated	d_2 () measured	M Calc.	M Meas.
10	20						
10	-6.67						

Experiment 3 (Optical instruments)

Sketch your microscope showing all distances:

Sketch your second microscope (with the $P = 10$ di objective):

Name: _____

Date: _____

Lab Partner: _____

Report Form: Geometric Optics (cont.)

Describe how your microscopes worked. Give the magnification and image characteristics.

Sketch your telescope, showing all distances.

Describe qualitatively what you see through the telescope pointing it out of the window (include any distortion, how wide a field of view you have, etc.):

Write out the text of the sign hanging on the tree:

For fun: Name at least one book by the author of the quotation on the sign (you must do this off the top of your head):