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Optical Instruments

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OPTICAL INSTRUMENTS

INTRODUCTION

You are now familiar with some of the properties of idealized single lenses and simple spherical and plane mirrors. Almost all optical instruments are made up of a combination of lenses, some close together and others far apart. Real lenses and mirrors have many undesirable properties intimately interconnected with their desirable properties. By making careful and clever combinations of lenses one can enhance the desirable and minimize the undesirable characteristics. In this module you will begin the study of some simple combinations of mirrors and simple lenses; it will give you some insight into the complications and fascinating possibilities of complex optical systems.

PREREQUISITES

Before you begin this module,
you should be able to:

Location of
Prerequisite Content

*Solve problems to find image or object location and lateral magnification by calculation and by ray diagram for spherical mirrors and thin lenses (needed for Objectives 1, 2, and 4 of this module)

Lenses
and Mirrors
Module

LEARNING OBJECTIVES

When you have mastered the content of this module, you will be able to:

1. Ray diagrams - Use ray diagrams to find magnification and locate objects, images, or lenses when appropriate other information is given for two-lens systems.
2. Lens equation - Use the thin-lens equation to find magnification and locate objects, images, or lenses when appropriate other information is given for two-lens systems.
3. Angular magnification - (a) Define angular magnification for various optical instruments. (b) Apply the definition of angular magnification to systems of two lenses, or one lens and one mirror, such as telescopes and compound microscopes.

TEXT: Frederick J. Bueche, Introduction to Physics for Scientists and Engineers (McGraw-Hill, New York, 1975), second edition

SUGGESTED STUDY PROCEDURE

Study the text Chapter 33, Sections 33.1, 33.3, and 33.4, and read the General Comments. Then study Problems A through F and work the Assigned Problems. To satisfy Objective 1 you should draw ray diagrams for the assigned problems even though they are not specifically requested. Study the ray diagrams in the study guide and Figure 33.5(b) in the text, but note that Figures 33.1, 33.4, and 33.5(a) are not ray diagrams. There is a minor notation problem that the following table should help.

	<u>Text</u>	<u>Study Guide</u>
Index of refraction	μ	n
Object distance	p	s
Image distance	p'	s'

BUECHE

Objective Number	Readings	<u>Problems with Solutions</u> Study Guide	<u>Assigned Problems</u>		Additional Problems (Chap. 33)
			Study Guide	Text (Chap. 33)	
1	Sec. 33.4	A, B	G		
2		C, D	G	13, 15, 17	14, 18
3	Secs. 33.1, 33.3, 33.4	E, F	H	8, 9, 11, 12	

TEXT: David Halliday and Robert Resnick, Fundamentals of Physics (Wiley, New York, 1970; revised printing, 1974)

SUGGESTED STUDY PROCEDURE

Since there is no discussion in your text specifically covering the objectives of this module, you can follow the study guide supplied by your tutor if you have one of the following texts available.

Frederick J. Bueche, Introduction to Physics for Scientists and Engineers (McGraw-Hill, New York, 1975), second edition.

Francis Weston Sears and Mark W. Zemansky, University Physics (Addison-Wesley, Reading, Mass., 1970), fourth edition. (Note that Sears and Zemansky use s and s' , instead of o and i for object and image distance, respectively.) Note also that most of the diagrams are not ray diagrams that follow the ray-construction rules.

TEXT: Francis Weston Sears and Mark W. Zemansky, University Physics (Addison-Wesley, Reading, Mass., 1970), fourth edition

SUGGESTED STUDY PROCEDURE

Study the text Chapter 40, Sections 40-5, 40-10, 40-13, and 40-14, and read the General Comments of the study guide. Study Problems A through F and ray diagrams, noting that most of the diagrams in the text are not strictly ray diagrams that follow the ray-construction rules. Work the Assigned Problems. To satisfy Objective 1, you should draw ray diagrams for all Assigned Problems, even though they are not specifically requested.

SEARS AND ZEMANSKY

Objective Number	Readings	Problems with Solutions	Assigned Problems		Additional Problems
		Study Guide	Study Guide	Text	
1		A, B	G		
2	Sec. 40-5	C, D	G	40-20, 40-21(a), 40-22	
3	Secs. 40-10, 40-13, 40-14	E, F	H	40-32, 40-33, 40-37, 40-38, 40-40	40-35, 40-39

TEXT: Richard T. Weidner and Robert L. Sells, Elementary Classical Physics (Allyn and Bacon, Boston, 1973), second edition, Vol. 2

SUGGESTED STUDY PROCEDURE

Study the text Chapter 37, Section 37-3 on lens combinations, and be sure to study Figures 37-16 through 37-20, as they are carefully drawn and merit careful study although little is said about them in the text. Read the General Comments. Study Problems A through F and work the Assigned Problems. You should draw ray diagrams for the assigned text problems even though it is not specifically suggested in the problem.

WEIDNER AND SELLS

Objective Number	Readings	Problems with Solutions	Assigned Problems	
		Study Guide	Study Guide	Text
1	Sec. 37-3	A, B	G	
2	Sec. 37-3	C, D	G	37-11, 37-12, 37-14
3	Sec. 37-3	E, F	H	37-17

GENERAL COMMENTS

Anyone who has a modest competence in geometrical optics has found ray diagrams essential for the understanding of optical systems. You have probably already discovered that remembering and correctly applying the sign conventions for the thin-lens equation can at times be difficult, and it gets worse for multiple-component systems. Drawing a ray diagram has fewer and less confusing rules. Ray diagrams provide a relatively independent check on the results of a calculation using the lens equations. Successful use of a ray diagram does require some practice, and you must draw several before trying a Mastery Test.

There is one case of two thin lenses that is particularly simple - when they are close enough together so that you can neglect the distance between them and when the object distance for the second lens is the negative of the image distance for the first lens. One of the Assigned Problems asks you to work out the details.

One experimental way to find the focal length of a converging lens is to set up an object and the lens and then find the location of the real image on a screen. A simple calculation using the object distance, image distance, and the thin-lens equation will then give you the focal length. This method cannot be used directly with a diverging lens because with normal diverging wavefronts a diverging lens cannot form a real image. Problems B and D illustrate a method of getting a real image with a diverging lens and thus a way to find its focal length.

Our ability to distinguish details depends in part upon the size of the image on our retina, which in turn depends on the angle subtended by the object at our eye. Thus to see an object more clearly we bring it closer to our eyes. There is a limit, however, because when it gets too close we can no longer focus on the object. We somewhat arbitrarily take 25 cm as the nearest distance of distinct vision, and characterize many optical instruments by their angular magnification. For a microscope, angular magnification (M) is defined as the ratio of the angle subtended by the image viewed by the eye to the angle subtended by the object at 25 cm. For a telescope, however, the angular magnification is defined as the ratio of the angle subtended by the image viewed by the eye to the angle subtended by the object at its actual location. These definitions are slightly different but reflect the actual use of the instrument. Note that the actual magnification will depend on the location of the final image, which in most instruments is adjustable.

PROBLEM SET WITH SOLUTIONS

A(1). Two thin converging lenses are on a common axis 1.00 m apart. The first lens (L_1) has a focal length $f_1 = +0.40$ m; the second lens (L_2) has a focal length $f_2 = +0.200$ m. An object 0.0200 m high is 0.90 m to the left of the first lens. Find the location and size of the final image by making a ray diagram.

Solution

To solve this problem draw a ray diagram, as you learned in the module Lenses and Mirrors, to find the image of the object as formed by the first lens. This is Figure 1. Now using the image formed by the first lens L_1 as the object for the

second lens, draw a ray diagram for the second lens, as in Figure 2. There is no need to use extensions of any of the rays from the ray diagram of L_1 . Ray diagrams in textbooks usually show particular rays continuing through both lenses, but that is not necessary.

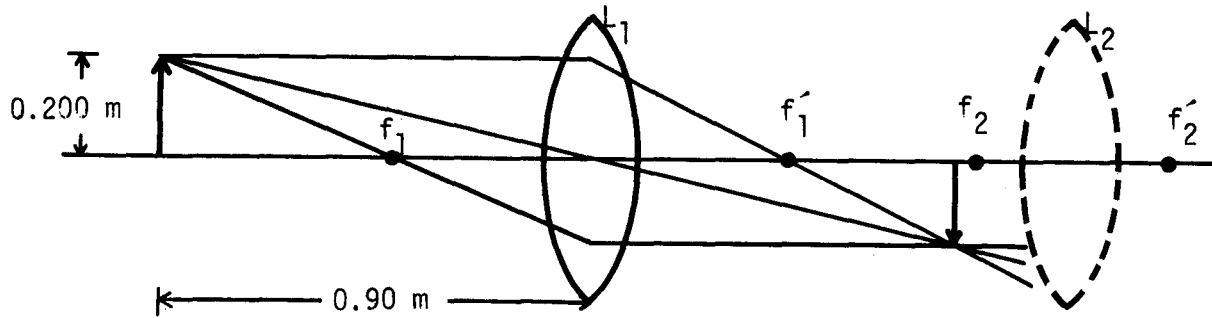


Figure 1

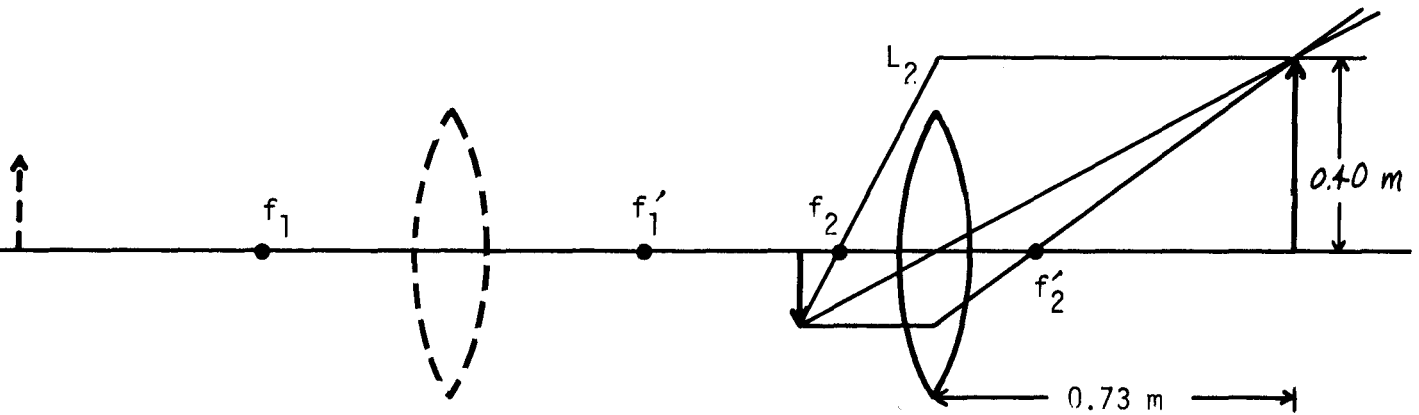


Figure 2

B(1). A thin converging lens (L_1) of focal length $f_1 = 0.40\text{ m}$ and a thin diverging lens (L_2) of focal length $f_2 = -0.300\text{ m}$ are on a common axis 1.00 m apart. An object 0.0100 m high is 0.60 m to the left of L_1 . Find the location and size of the final image by making a ray diagram.

Solution

As in Problem A find the image formed by the first lens: See Figure 3. The next step is a bit tougher, however: we cannot treat the image from L_1 as a simple

object for L_2 because its rays are intercepted by L_2 before they can form an image (virtual object). We shall proceed by choosing very carefully the rays that we will draw.

- (1) A parallel ray headed toward a virtual object point will diverge from f_2 .
- (2) A ray headed for f_2' and a virtual object point will be refracted parallel to the axis.
- (3) A ray passing through the center of the lens and heading for a virtual object point will be undeflected.

Note that on a ray diagram, you may use rays refracted by an extension of the lens. See Figure 4.

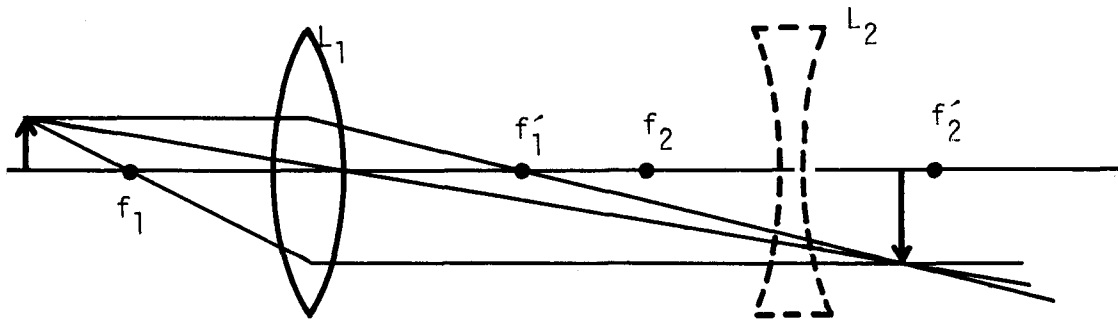


Figure 3

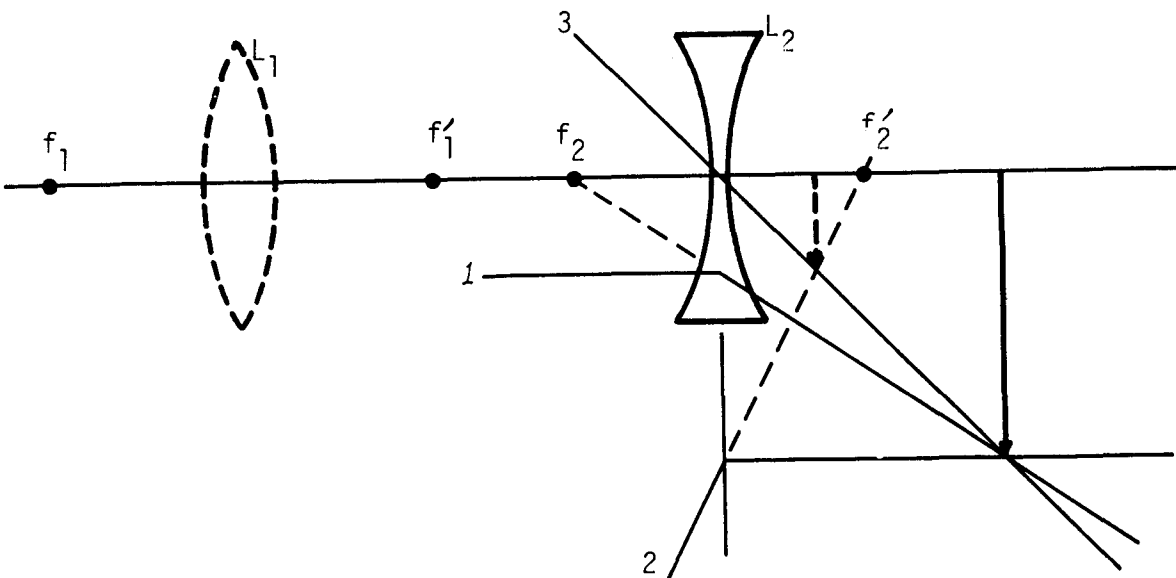


Figure 4

C(2). For the same conditions as in Problem A, find the location and size of the final image by calculation.

Solution

Apply the approximate thin-lens equation to find the image location of the original object as formed by the first lens:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f_1}, \quad \frac{1}{0.90} + \frac{1}{s'} = \frac{1}{0.40}, \quad s' = 0.72 \text{ m.}$$

From similar triangles on the ray diagram or the formula for lateral magnification,

$$\text{image size} = -(s'/s)(\text{object size}) = (0.72/0.90)(0.0200) = -0.0160 \text{ m.}$$

The negative simply implies an inverted image. Since the lenses are 1.00 m apart, the image from L_1 is now the object for L_2 and has an object distance

$$s_2 = 1.00 - 0.72 = 0.280 \text{ m.}$$

We now apply the thin-lens equation again:

$$\frac{1}{s_2} + \frac{1}{s_2'} = \frac{1}{f_2}, \quad \frac{1}{0.280} + \frac{1}{s_2'} = \frac{1}{0.200}, \quad s_2' = 0.70 \text{ m,}$$

$$\text{final image size} = -(-0.0160)(0.70/0.280) = 0.040 \text{ m.}$$

These results agree quite closely with the graphical solution to Problem A.

D(2). Work Problem B using the thin-lens equation.

Solution

The location and size of the image formed by the first lens should be fairly routine by now:

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f_1}, \quad \frac{1}{0.60} + \frac{1}{s'} = \frac{1}{0.40}, \quad s' = 1.20 \text{ m;}$$

$$\text{image height} = -(s'/s)(\text{object height}) = -\frac{1.20}{0.60}(0.0100) = -0.0200 \text{ m.}$$

This image now becomes the object for L_2 , its object distance

$$s_2 = 1.00 - 1.20 = -0.200 \text{ m.}$$

The negative sign indicates a virtual object.

$$\frac{1}{s_2} + \frac{1}{s_2'} = \frac{1}{f_2}, \quad \frac{1}{-0.200} + \frac{1}{s_2'} = \frac{1}{-0.300}, \quad s_2' = 0.60 \text{ m;}$$

$$\text{image height} = -(s_2'/s_2)(\text{object height}) = -[0.60/(-0.200)](-0.0200) = -0.060 \text{ m.}$$

This result agrees with the result from the lens diagram in Problem B.

- E(3). The Moon at a distance of 3.8×10^8 m subtends an angle of $\sim 0.5^\circ$ as seen from the Earth. With a telescope objective lens L_1 of focal length 2.00 m:
- Find the image I_1 , location, and size.
 - A converging lens L_2 ($f = 5.0$ cm) is used to view the image I_1 created by the objective lens. The final image I_2 is virtual and 0.250 m from L_2 . Find the distance from image I_1 to L_2 .
 - What angle does the image I_1 subtend at the lens L_2 ?
 - What angle does the image I_2 subtend at the lens L_2 ?
 - What is the angular magnification of this simple telescope?

Solution

(a) From the thin-lens equation, since the object distance is very large the image will be at $f = 2.00$ m. The image and object of a thin lens subtend equal angles; thus, $\theta = y/f$, where y is the image size:

$$y = f\theta = (2.00 \text{ m})(0.5^\circ) = (2.00 \text{ m})(0.00873 \text{ rad}) = 0.0175 \text{ m}.$$

(b) For L_2 , s_2 is unknown. $s' = -0.250$ m, $f = 0.050$ m,

$$\frac{1}{s_2} - \frac{1}{0.250} = \frac{1}{0.050}, \quad s_2 = 0.042 \text{ m}.$$

(c) The angle subtended,

$$\tan \theta_2 = y/s_2 = 0.0174/0.042 = 0.42, \quad \theta_2 = 0.40 \text{ rad} = 22.7^\circ.$$

Since we have frequently used the small-angle approximation, we could equally as well have said $\theta_2 = y/s_2 = 0.42$.

(d) The image subtends the same angle as the object:

$$\theta_2' = \theta_2 = 0.40 \text{ rad} = 22.7^\circ.$$

(e) $M = \theta_2'/\theta = 22.7/0.50 = 45$. Notice that this corresponds roughly to the approximate formula

$$M = f_o/f_e = 2.00/0.050 = 40$$

(derived for the final image at infinity).

- F(3). A compound microscope has an objective lens L_1 , of focal length 4.0 mm. It forms an image I_1 at a distance of 16.0 cm of an object of 10^{-5} m diameter. It is viewed by a simple eyepiece (L_2 , $f_2 = 2.50$ cm) adjusted to form a virtual image I_2 at infinity.
- Find the angle subtended by the object at the closest distance of distinct vision.
 - How large is the image I_1 ?
 - What angle does the image I_1 subtend at L_2 when the final image I_2 is at infinity?
 - What angle does I_2 subtend at L_2 ?
 - Find the angular magnification of the microscope.

Solution

(a) $\tan \theta \approx \theta = 10^{-5}/0.250 = 4.0 \times 10^{-5}$ rad.

(b) The image size = (object size)(s_1'/s_1) = $10^{-5}(0.160/0.0041) = 3.9 \times 10^{-4}$ m.
The object distance will be slightly larger than f_1 :

$$\frac{1}{s_1} + \frac{1}{0.160} = \frac{1}{0.0040}, \quad s_1 = 0.0041.$$

(c) For I_2 at infinity s_2 , the object distance, is $f_2 = 0.025$ m. Thus,

$$\theta_2 = (3.9 \times 10^{-4})/0.0250 = 0.0156 \text{ rad.}$$

(d) Same as part (c), 0.0156 rad.

(e) $M = \theta_2/\theta = 0.0156/(4.0 \times 10^{-5}) = 390.$

Problems

- G(1, 2). A thin diverging lens, $f_1 = -0.40$ m, and a thin converging lens, $f_2 = 0.200$ m, are on a common axis 0.100 m apart. An object 0.040 m high is located 0.40 m to the left of the diverging lens. Find the location and size of the final image by a ray diagram and by calculation from the thin-lens equation.
- H(3). A Galilean telescope is to be constructed using an objective lens L_1 of $f_1 = +0.40$ m and a diverging lens L_2 of focal length $f_2 = -0.050$ m.

- (a) What angle is subtended by a 2.00-m object at 100 m distance?
- (b) How large an image will be formed by lens L_1 ?
- (c) The diverging lens L_2 is placed so that the final image I_2 is a virtual image at infinity. Find the angle subtended by the virtual object I_1 at L_2 .
- (d) Find the angle subtended by I_2 at L_2 .
- (e) Find the angular magnification M for the Galilean telescope adjusted as above.

Solutions

G(1, 2). Location: 0.60 m to the right of the converging lens. Size: 0.040 m high.

H(3). 0.0200 rad. (b) 0.0080 m. (c) 0.160 rad. (d) 0.160 rad. (e) 7.9.

PRACTICE TEST

1. Two thin lenses each of focal length +20.0 cm are 20.0 cm apart. An object is 10.0 cm to the left of the left-hand lens. Find the location of the final image by both a ray diagram and calculation using the thin-lens equation.
2. Define angular magnification for a microscope.
3. An opera glass consists of a converging lens of focal length 0.60 m and a diverging lens of focal length -0.100 m. Find the angular magnification for a 2.00-m tall opera singer at a distance of 30.0 m. (If you use any simple formulas for angular magnification be sure that you derive them.) Assume the final image to be at infinity.

3. 5.8.

2. The ratio of the angle subtended by the final image at the ocular, to the angle subtended by the object at 25 cm.

1. 40 cm right of right-hand lens.

Practice Test Answers