30 Lenses

A light ray bends as it enters glass and bends again as it leaves. The bending, or refraction, is due to the difference in the speed of light in glass and in air. Glass of certain shapes can form images which appear larger, smaller, closer, or farther than the object being viewed. Magnifying glasses have been used for centuries and were well known to the early Greeks and medieval Arabs. Today, eyeglasses allow millions of people to read in comfort, and cameras, projectors, telescopes, and microscopes widen our view of the world.

30.1 Converging and Diverging Lenses

If a piece of glass has just the right shape, it can bend parallel rays of light so that they all cross—or appear to have crossed—at a single point. A piece of glass that does this is called a **lens**.

The special shape of a lens can be understood by considering a lens to be a large number of portions of triangular prisms (Figure 30–1). When arranged properly, the prisms refract incoming parallel rays so they converge to (or diverge from) a single point. The arrangement shown at the left is thicker in the middle and converges the light. The arrangement at the right, however, is thinner in the middle than at the edges; it diverges the light.

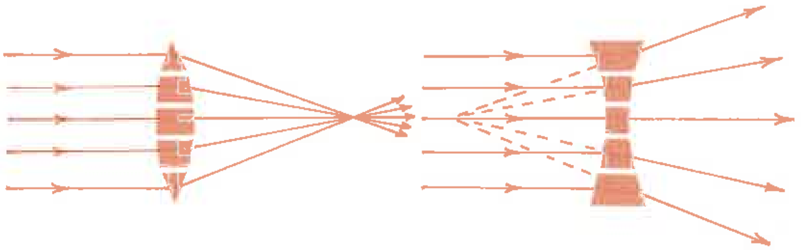

Fig. 30–1 A lens may be thought of as a set of prisms that converge light (left) or diverge light (right).

In both arrangements, the greatest net bending of rays occurs at the outermost prisms, for they have the greatest angle between the two refracting surfaces. No net bending occurs in the middle "prism," for its glass faces are parallel to each other, and a ray emerges in its original direction.

Real lenses are made not of prisms, of course, but of solid pieces of glass with surfaces ground usually to a spherical curve. Figure 30–2 shows how smooth lenses refract rays of light and wave fronts. The lens at the left is thicker in the middle and converges parallel rays of light (straight wave fronts). It is called a **converging lens**. The lens at the right is thinner in the middle and diverges parallel rays of light. It is called a **diverging lens**.

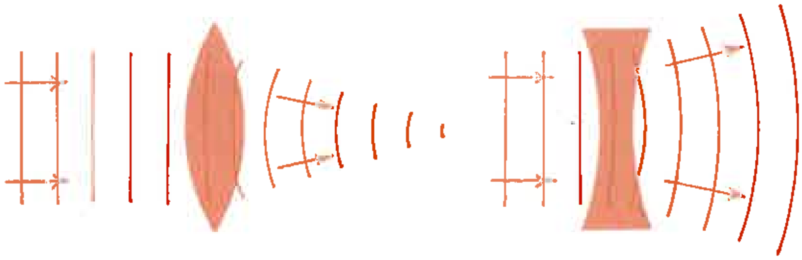

Fig. 30–2 Wave fronts travel more slowly in glass than in air. In the converging lens (left), the wave fronts are retarded more through the center of the lens, and the light converges. In the diverging lens (right), the waves are retarded more at the edges, and the light diverges.

Figure 30–3 illustrates some important terms for a lens. The **principal axis** of a lens is the line joining the centers of curvatures of its surfaces. For a converging lens, the **focal point** is the point at which a beam of parallel light, parallel to the principal axis, converges. Incident parallel beams that are not parallel to the principal axis focus at points above or below the focal point. All such possible points make up a **focal plane**. Since a lens has two surfaces, it has two focal points and two focal planes. When the lens of a camera is set for distant objects, the film is in the focal plane behind the lens in the camera.

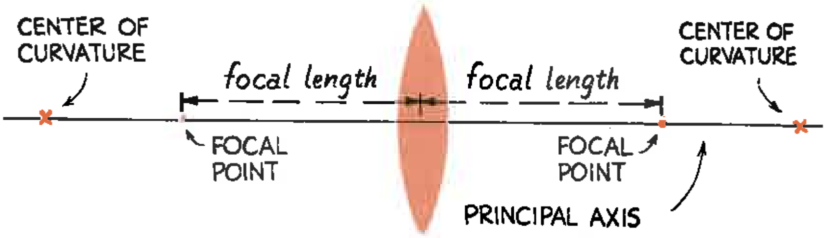

Fig. 30–3 Key features of a converging lens.

For a diverging lens, an incident beam of light parallel to the principal axis is not converged to a point, but is diverged so that the light appears to come from a point in front of the lens. The **focal length** of a lens, whether converging or diverging, is the distance between the center of the lens and its focal point. When the lens is thin, the focal lengths on either side are equal, even when the curvatures on the two sides are not.

30.2 Image Formation by a Lens

With unaided vision, an object far away is seen through a relatively small angle of view, while the same object when closer is seen through a larger angle of view. This wider angle enables the perception of more detail. Magnification occurs when an image is observed through a wider angle with the use of a lens than without the lens. A magnifying glass is simply a converging lens that increases the angle of view.

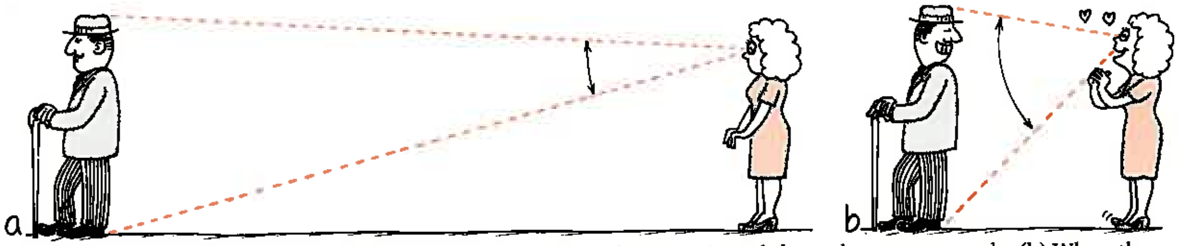

Fig. 30–4 (a) A distant object is viewed through a narrow angle. (b) When the same object is viewed through a wide angle, more detail is seen.

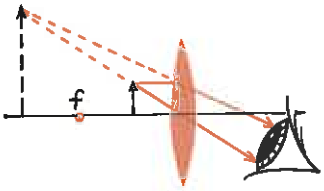

Fig. 30–5 A converging lens can be used as a magnifying glass to produce a virtual image of a nearby object. The image appears larger and farther from the lens than the object.

When you use a magnifying glass, you hold it close to the object you wish to see magnified. This is because a converging lens will magnify only when the object is between the focal point and the lens. The magnified image will be farther from the lens than the object, and it will be right-side-up. If a screen were placed at the image distance, no image would appear on the screen. This is because no light is actually directed to the image position. The rays that reach your eye, however, behave virtually as if they did, so the image is a virtual image.

When the object is far enough away to be beyond the focal point of a converging lens, light from the object does converge and can be focused on a screen (Figure 30–6). An image formed by converging light is called a **real image**. A real image formed by a single converging lens is upside down (inverted). Converging lenses are used for projecting slides and motion pictures on a screen, and for projecting a real image on the film of a camera.

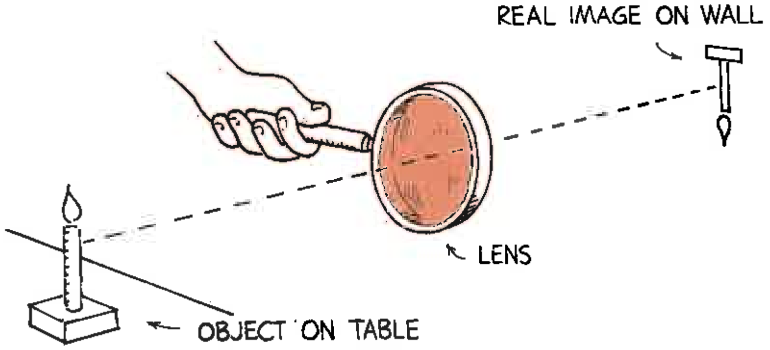

Fig. 30–6 A converging lens forms a real, upside-down image of a more distant object.

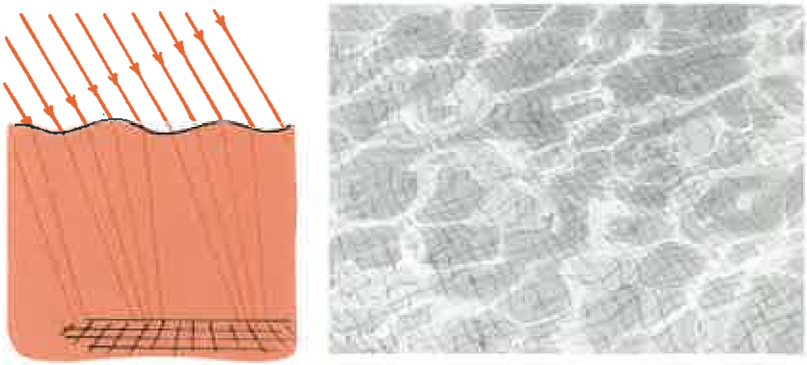

Fig. 30–7 The moving pattern of bright lines on the bottom of a swimming pool results from the uneven surface of water, which behaves as a moving blanket of converging lenses.

When a diverging lens is used alone, the image is always virtual, right-side-up, and smaller than the object. It makes no difference how far or how near the object is. A diverging lens is often used as a viewfinder on a camera. When you look at the object to be photographed through the viewfinder, you see a virtual image that approximates the same proportions as the photograph.

Fig. 30–8 A virtual image produced by a diverging lens.

▶ **Question**

Why is the greater part of the photograph in Figure 30–8 out of focus?

▶ **Answer**

Both Jamie and his cat and the virtual image of Jamie and his cat are "objects" for the lens of the camera that took this photograph. Since the objects are at different distances from the camera lens, their respective images are at different distances with respect to the film in the camera. So only one can be brought into focus. The same is true of your eyes. You cannot focus on near and far objects at the same time.

30.3 Constructing Images Through Ray Diagrams

Ray diagrams, like the one in Figure 30–9, show the principal rays that can be used to determine the size and location of an image. The size and location of the object, its distance from the center of the lens, and the focal length of the lens must be known.* An arrow is used to represent the object (which may be anything from a microbe viewed in a microscope to a galaxy viewed through a telescope). For simplicity, one end of the object is placed right on the principal axis.

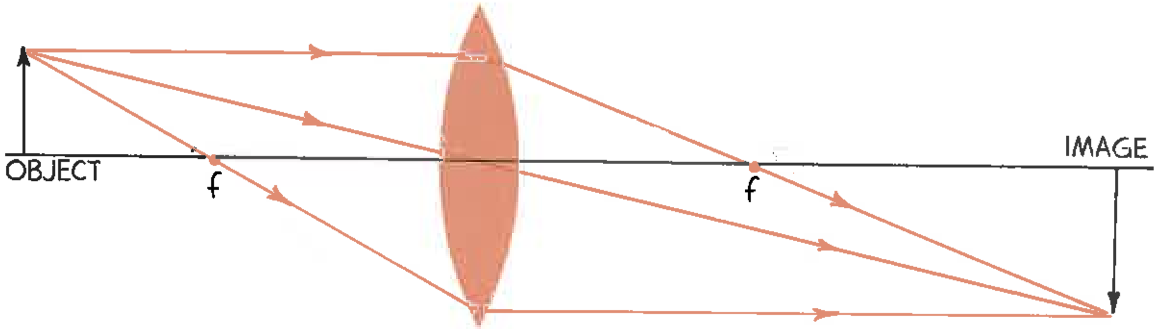

Fig. 30–9 Ray diagram. Three useful rays from the object that converge on the image.

To locate the position of the image, you have to know only the paths of two rays from a point on the object. Any point will work, but it is customary to choose a point at the tip of the arrow.

The path of one refracted ray is known from the definition of the focal point. A ray parallel to the principal axis will be refracted by the lens to the focal point, as shown in Figure 30–9.

Another path is known: through the center of the lens where the faces are parallel to each other. A ray of light will pass through the center with no appreciable change in direction. Therefore a ray from the tip of the arrowhead proceeds in a straight line through the center of the lens.

A third path is known: A ray that passes through the focal point in front of the lens emerges from the lens parallel to the principal axis.

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* The mathematical relationship between object distance o, image distance i, and focal length f is given by

$$\frac{1}{o}+\frac{1}{i}=\frac{1}{f}$$

This is called the *thin-lens equation*.

All three paths are shown in Figure 30–9, which is a typical ray diagram. The image is located where the three rays intersect. Any two of these three rays is sufficient to locate the relative size and location of the image.

The ray diagram for a converging lens used as a magnifying glass is shown in Figure 30–10. In this case, where the object is within one focal length of the lens, the rays diverge as they leave the lens. They appear to come from a point in front of the lens (same side of the lens as the object). The location of the image is found by extending the rays to the point where they converge. The virtual image is magnified and right-side-up.

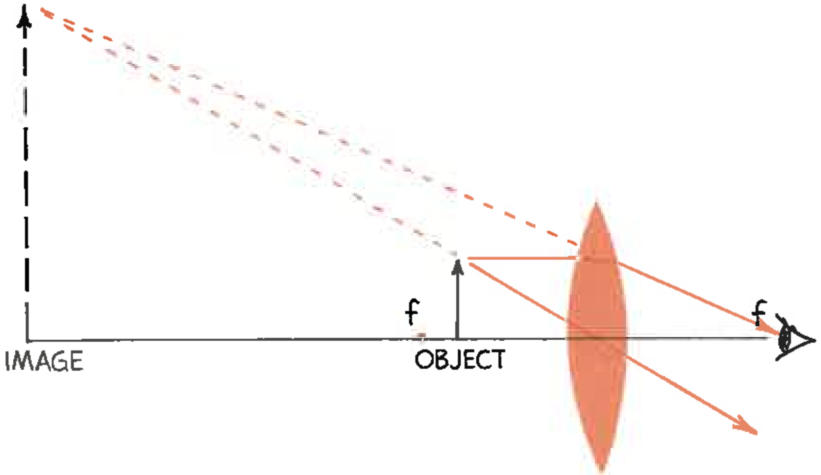

Fig. 30–10 Ray diagram for a magnifying glass. The object is within one focal length of the lens, so the image is virtual, right-side-up, and magnified.

The three rays useful for the construction of a ray diagram are summarized:

1. A ray parallel to the principal axis which passes through the focal point after refraction by the lens.
2. A ray through the center of the lens which does not change direction.
3. A ray through the focal point in front of the lens which emerges parallel to the principal axis after refraction by the lens.

Any two rays are sufficient to locate an image; which particular pair is chosen is merely a matter of convenience.

The ray diagrams in Figure 30–11 show image formation by a converging lens as an object initially at the focal point is moved away from the lens along the principal axis. Since the object is not within one focal length, all the images are real and inverted.

Object position: distance *f* from lens (at the focal point)
Image position: at infinity

Object position: between *f* and 2*f* from lens
Image position: beyond 2*f* from lens
Image size: magnified

Object position: distance 2*f* from lens
Image position: distance 2*f* from lens
Image size: same as object

Object position: beyond 2*f* from lens
Image position: between *f* and 2*f* from lens
Image size: smaller

Object position: at infinity
Image position: distance *f* from lens (at the focal point)

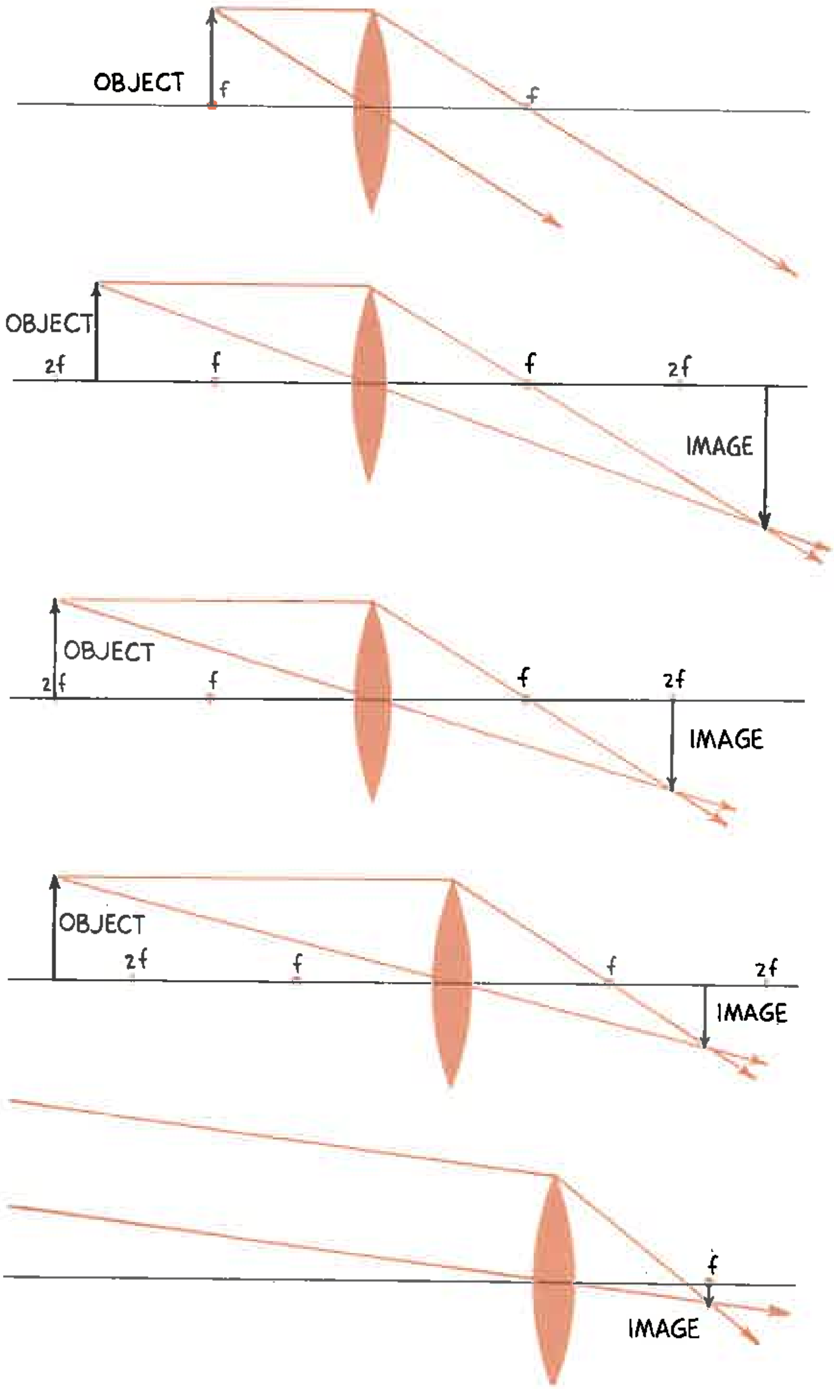

Fig. 30–11 Ray diagrams for different positions of an object in relation to a converging lens of focal length *f*.

The method of drawing ray diagrams applies also to diverging lenses (Figure 30–12). A ray parallel to the principal axis from the tip of the arrow will be bent by the lens in the same direction as if it had come from the focal point. A ray through the center goes straight through. A ray that is heading for the focal point on the far side of the lens is bent so that it emerges parallel to the lens.

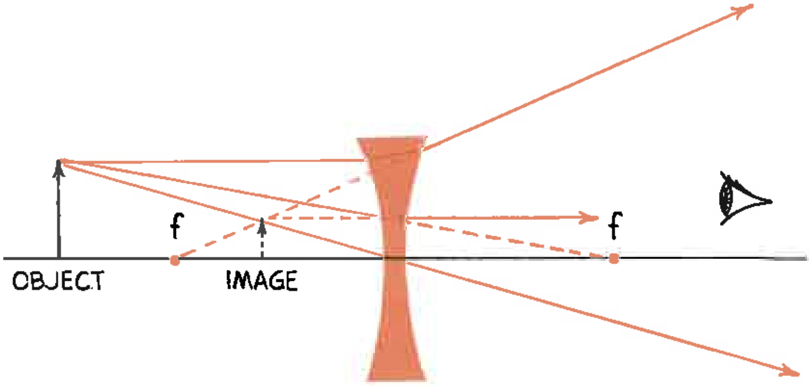

Fig. 30–12 Ray diagram for a diverging lens.

On emerging from the lens, the three rays appear to come from a point on the same side of the lens as the object. This point defines the position of the virtual image. The image is nearer the lens than the object. It is smaller than the object and right-side-up. Regardless of the object position, the image formed by a diverging lens is always virtual, reduced, and right-side-up.

30.4 Image Formation Summarized

A converging lens is a simple magnifying glass when the object is within one focal length of the lens. The image is then virtual, magnified, and right-side-up.

When the object is beyond one focal length, a converging lens produces a real, inverted image. The location of the image depends on how close the object is to the focal point. If it is close to the focal point, the image is far away (as with a slide projector or movie projector). If the object is far from the focal point, the image is nearer (as with a camera). In all cases where a real image is formed, the object and the image are on opposite sides of the lens.

When the object is viewed with a diverging lens, the image is virtual, reduced, and right-side-up. This is true for all locations of the object. In all cases where a virtual image is formed, the object and the image are on the same side of the lens.

▶ **Question**

Where must an object be located so that the image formed by a converging lens will be (a) at infinity? (b) As near the object as possible? (c) Right-side-up? (d) The same size? (e) Inverted and enlarged?

30.5 Some Common Optical Instruments

Many optical instruments use lenses. Among these are the camera, telescope (and binoculars), compound microscope, and projector.

The Camera

A camera consists of a lens and sensitive film mounted in a light-tight box. In many cameras, the lens is mounted in a screw mount which can be moved to or fro to adjust the distance between the lens and film. The lens forms a real, inverted image on the film.

Figure 30–13 shows a camera with a single simple lens. In practice, most cameras make use of compound lenses to minimize distortions called *aberrations*.

The amount of light that gets to the film is regulated by a shutter and a diaphragm. The shutter controls the length of time that the film is exposed to light. The diaphragm controls the opening that light passes through to reach the film. Varying the size of the opening (aperture) varies the amount of light that reaches the film at any instant.

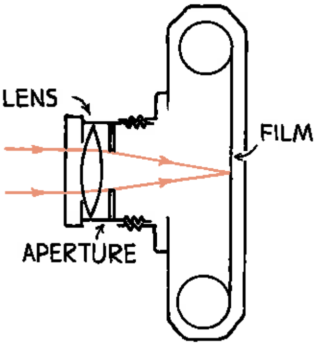

Fig. 30–13 A simple camera.

The Telescope

A **telescope** uses a lens to form a real image of a distant object. The real image is not caught on film but is projected in space to be examined by another lens used as a magnifying glass. The second lens, called the **eyepiece**, is positioned so that the image produced by the first lens is within one focal length. The eyepiece forms an enlarged virtual image of the real image. When you look through a telescope, you are looking at an image of an image.

▶ **Answer**

The object should be (a) one focal length from the lens (at the focal point) (see Figure 30–11); (b) and (c) within one focal length of the lens (see Figure 30–10); (d) at two focal lengths from the lens (see Figure 30–11); (e) between one and two focal lengths from the lens (see Figure 30–11).

Figure 30–14 shows the lens arrangement for an *astronomical telescope*. The image is inverted, which explains why maps of the moon are printed with the moon upside down.

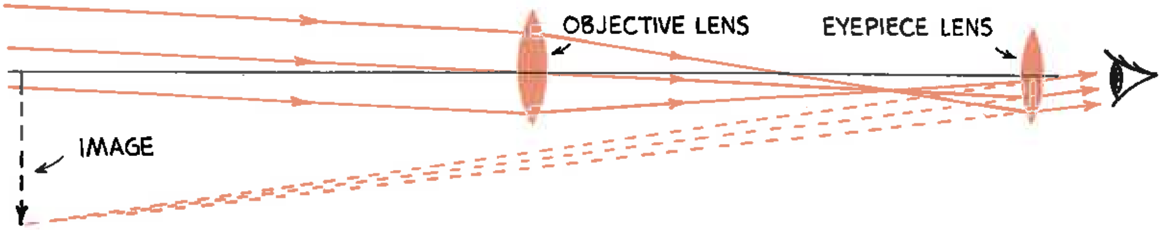

Fig. 30–14 Lens arrangement for an astronomical telescope. (For simplification, the image is shown close here; it is actually located at infinity.)

A third lens or a pair of reflecting prisms is used in the *terrestrial telescope*, which will produce an image that is right-side-up. A pair of these telescopes side by side, each with a pair of prisms to provide four reflecting surfaces to turn images right-side-up, makes up a pair of *binoculars* (Figure 30–15).

Since no lens transmits 100% of the light incident upon it, astronomers prefer the brighter, inverted images of a two-lens telescope to the less bright, right-side-up images that a third lens or prisms would provide. For nonastronomical uses, such as viewing distant landscapes or sporting events, right-side-up images are more important than brightness, so the additional lens or prisms are used.

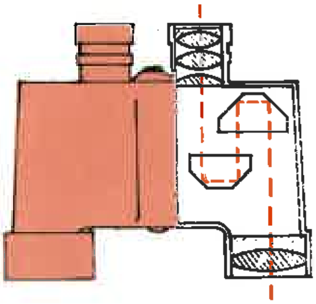

Fig. 30–15 The arrangement of prisms in binoculars.

The Compound Microscope

A compound microscope uses two converging lenses of short focal length, arranged as shown in Figure 30–16. The first lens, called the **objective lens**, produces a real image of a close object. Since the image is farther from the lens than the object, it is enlarged. A second lens, the eyepiece, forms a virtual image of the first image, further enlarged. The instrument is called a compound microscope because it enlarges an already enlarged image.

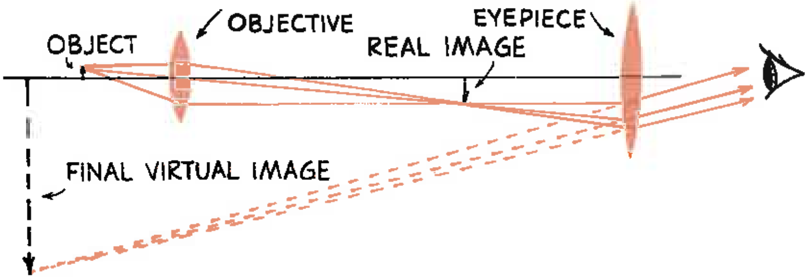

Fig. 30–16 Lens arrangement for a compound microscope.

The Projector

The arrangement of converging lenses for a slide or movie projector is shown in Figure 30–17. A concave mirror reflects light from an intense source back onto a pair of *condenser lenses*. The condenser lenses direct the light through the slide or movie frame to a *projection lens*. The projection lens is mounted in a sliding tube so that it can be positioned to or fro to focus a sharp image on the screen.

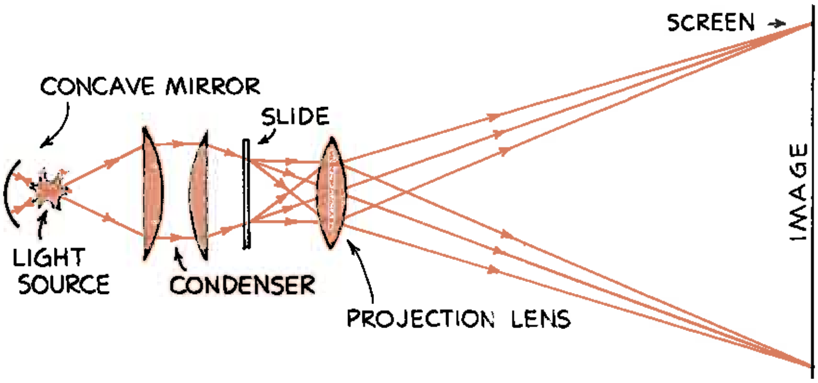

Fig. 30–17 Lens arrangement for a projector.

30.6 The Eye

In many respects the human eye is similar to the camera. The amount of light that enters is regulated by the **iris**, the colored part of the eye which surrounds the opening called the **pupil**.* Light enters through the transparent covering called the **cornea**, passes through the pupil and lens, and is focused on a layer of tissue at the back of the eye—the **retina**—that is more sensitive to light than any artificial detector made. Different parts of the retina receive light from different directions.

The retina is not uniform. There is a small region in the center of our field of view at which we have the most distinct vision. This spot is called the *fovea*. Much greater detail can be seen here than at the side parts of the eye.

There is also a spot in the retina where the nerves carrying all the information run out. This is the *blind spot*. You can demon-

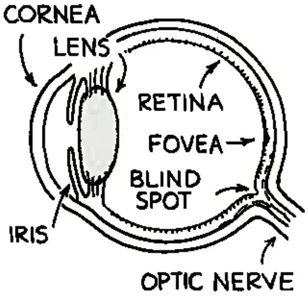

Fig. 30–18 The human eye.

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* The hole of the pupil usually looks black because light is going in but not coming out. Sometimes in flash photos, the light from the flashbulb enters the eye at just the right angle to reflect off the retina at the back of the eye. That's why flash photographs sometimes show the pupils to be pinkish.

strate that you have a blind spot in each eye if you hold this book at arm's length, close your left eye, and look at the circle in Figure 30–19 with only your right eye. You can see both the circle and the X at this distance. If you now move the book slowly toward your face, with your right eye still fixed upon the circle, you'll reach a position about 20 to 25 cm from your eye where the X disappears. To establish the blind spot in your left eye, close your right eye and similarly look at the X with your left eye so that the circle disappears. With both eyes opened, you'll find no position where either the X or circle disappears because one eye "fills in" the part of the object to which the other eye is blind. It's nice to have two eyes.

Fig. 30–19 For the blind spot experiment.

In both the camera and the eye, the image is upside down, and this is compensated for in both cases. You simply turn the camera film around to look at it. Your brain has learned to turn around images it receives from your retina!

A principal difference between a camera and the human eye has to do with focusing. In a camera, focusing is accomplished by altering the distance between the lens and the film. In the human eye, most of the focusing is done by the cornea, the transparent membrane at the outside of the eye. Adjustments in focusing of the image on the retina are made by changing the thickness and shape of the lens to regulate its focal length. This is called *accomodation* and is brought about by the action of the *ciliary muscle*, which surrounds the lens.

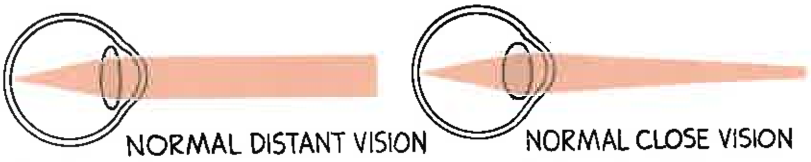

Fig. 30–20 The shape of the lens changes to focus light on the retina.

30.7 Some Defects in Vision

If you have what is called normal vision, your eye can accomodate to clearly see objects from infinity (the *far point*) down to 25 cm (the *near point*, which normally recedes for all people with advancing age).

The eyes of a **farsighted** person form images behind the retina (Figure 30–21). The eyeball is too short. Farsighted people have to hold things more than 25 cm away to be able to focus them. The remedy is to increase the converging effect of the eye. This is done by wearing eyeglasses or contact lenses with converging lenses. Converging lenses will converge the rays that enter the eye sufficiently to focus them on the retina instead of behind the retina.

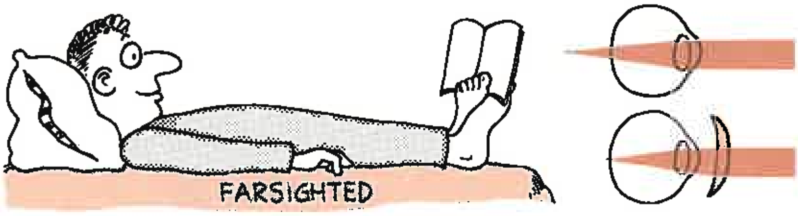

Fig. 30–21 The eyeball of the farsighted eye is too short. A converging lens moves the image closer and onto the retina.

A **nearsighted** person can see nearby objects clearly, but does not see distant objects clearly because they are focused too near the lens, in front of the retina (Figure 30–22). The eyeball is too long. A remedy is to wear corrective lenses that diverge the rays from distant objects so that they focus on the retina instead of in front of it.

Fig. 30–22 The eyeball of the nearsighted eye is too long. A diverging lens moves the image farther away and onto the retina.

Astigmatism of the eye is a defect that results when the cornea is curved more in one direction than the other, somewhat like the side of a barrel. Because of this defect, the eye does not form sharp images. The remedy is cylindrical corrective lenses that have more curvature in one direction than in another.

30.8 Some Defects of Lenses

No lens gives a perfect image. The distortions in an image are called **aberrations**. By combining lenses in certain ways, aberrations can be minimized. For this reason, most optical instruments use compound lenses, each consisting of several simple lenses, instead of single lenses.

Spherical aberration results when light passes through the edges of a lens and focuses at a slightly different place from light passing through the center of the lens (Figure 30–22). This can be remedied by covering the edges of a lens, as with a diaphragm in a camera. Spherical aberration is corrected in good optical instruments by a combination of lenses.

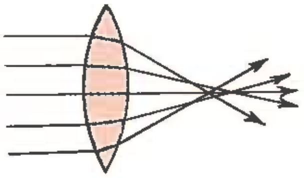

Fig. 30–23 Spherical aberration.

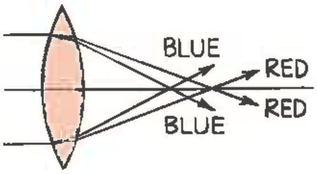

Fig. 30–24 Chromatic aberration.

Chromatic aberration is the result of the different speeds of various colors and hence the different refractions they undergo. In a simple lens (as in a prism), red light and blue light do not come to focus in the same place. *Achromatic lenses*, which combine simple lenses of different kinds of glass, correct this defect.

In the eye, vision is sharpest when the pupil is smallest because light then passes through only the center of the eye's lens, where spherical and chromatic aberrations are minimal. Also, light bends the least through the center of a lens, so minimal focusing is required for a sharp image. An image that is formed by straight lines of light can appear in focus anywhere. You see better in bright light because your pupils are smaller.*

▶ Question

Why is there chromatic aberration in light that passes through a lens, but no chromatic aberration in light that reflects from a mirror?

An option to poor sight in the last five hundred years has been to wear spectacles, and in more recent times an option to wearing spectacles has been to wear contact lenses. It is interesting to note that at the present time there is an option to both spectacles and contact lenses for people with poor eyesight. Experimental and controversial techniques today allow eye surgeons to reshape the cornea of the eye for normal vision. In tomorrow's world, the wearing of eyeglasses and contact lenses may be a thing of the past. We really do live in a rapidly changing world. And that can be nice.

▶ Answer

Different frequencies travel at different speeds in a transparent medium, and therefore refract at different angles, which produces chromatic aberration. The angles at which light *reflects*, on the other hand, have nothing to do with the frequency of light. One color reflects the same as any other. Mirrors are therefore preferable to lenses in telescopes because there is no chromatic aberration with reflection.

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* If you wear glasses and ever misplace them, or find it difficult to read small print, as in a telephone book, hold a pinhole (in a piece of paper or whatever) in front of your eye close to the page. You'll see the print clearly, and because you're close, it will seem magnified. Try it and see!

30 Chapter Review

Concept Summary

A lens refracts parallel rays of light so that they cross—or appear to cross—at a focal point.

- A converging lens is thicker in the middle; a diverging lens is thinner in the middle.
- A converging lens forms virtual, magnified images when the object is within one focal length of the lens.
- A converging lens forms real images when the object is beyond one focal length from the lens.
- A diverging lens always forms virtual, reduced images.
- Optical instruments that use lenses include the camera, telescope, compound microscope, and projector.
- The human eye refracts light and focuses it on the retina (with the help of corrective lenses if necessary).

Important Terms

aberration (30.8)
astigmatism (30.7)
converging lens (30.1)
cornea (30.6)
eyepiece (30.5)
diverging lens (30.1)
farsighted (30.7)
focal length (30.1)
focal plane (30.1)
focal point (30.1)
iris (30.6)
lens (30.1)
nearsighted (30.7)
objective lens (30.5)
principal axis (30.1)
pupil (30.6)
ray diagram (30.3)
real image (30.2)
retina (30.6)
telescope (30.5)

Review Questions

1. Distinguish between a *converging* lens and a *diverging* lens. (30.1)
2. Distinguish between the focal *point* and focal *plane* of a lens. (30.1)
3. Distinguish between a *virtual* image and a *real* image. (30.2)
4. There are three convenient rays commonly used in ray diagrams to estimate the position of an image. Describe these three rays in terms of their orientation with respect to the principal axis and focal points. (30.3)
5. How many of the rays in Question 4 are necessary for estimating the position of an image? (30.3)
6. Do ray diagrams apply only to converging lenses, or to diverging lenses as well? (30.3)
7. Explain what is meant by saying that in a telescope one looks at the image of an image? (30.5)
8. In what two ways does an astronomical telescope differ from a terrestrial telescope? (30.5)
9. How does a compound microscope differ from a telescope? (30.5)
10. Which instrument—a telescope, a compound microscope, or a camera—is most similar to the eye? (30.5–30.6)
11. Why do you not normally see a blind spot when you look at your surroundings? (30.6)
12. Distinguish between *farsighted* and *nearsighted* vision. (30.7)

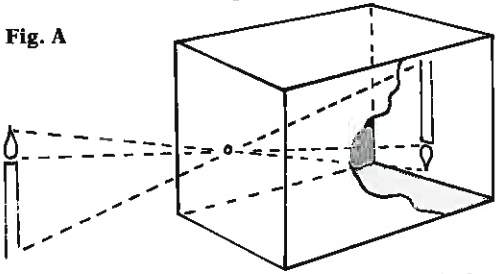
13. What is astigmatism, and how can it be corrected? (30.7)

14. Distinguish between *spherical* aberration and *chromatic* aberration, and cite a remedy for each. (30.8)

Activities

1. Make a pinhole camera, as illustrated in Figure A. Cut out one end of a small cardboard box, and cover the end with tissue or onionskin paper. Make a clean-cut pinhole at the other end. (If the cardboard is thick, place a piece of metal foil over an opening in the cardboard, and make the hole in the foil.) Aim the camera at a bright object in a darkened room, and you will see an upside-down image on the translucent tissue paper. If in a dark, windowless room you replace the tissue paper with unexposed photographic film, cover the back so it is light-tight, and cover the pinhole with a removable flap, you are now ready to take a picture. Exposure times differ depending mostly on the kind of film and the amount of light. Try different exposure times, starting with about 3 seconds. Also try boxes of various lengths. You'll find everything in focus in your photographs, but the pictures will not have clear-cut sharp outlines. The principal difference between your pinhole camera and a commercial one is the glass lens, which is larger than the pinhole and therefore admits more light in less time. It is because a lens camera is so fast that the pictures it takes are called "snapshots."

Fig. A



2. Look at the reflections of overhead lights from the two surfaces of eyeglasses, and you will see two fascinatingly different images. Why are they different?

3. Determine the magnification power of a lens by focusing on the lines of a ruled piece of paper (Figure B). Count the spaces between the lines that fit into one magnified space, and you have the magnification power of the lens. For example, if three spaces fit into one magnified space, then the magnification power of the lens is 3. You can do the same with binoculars and a distant brick wall. Hold the binoculars so that only one eye looks at the bricks through the eyepiece while the other eye looks directly at the bricks. The number of bricks, as seen with the unaided eye, that will fit into one magnified brick gives the magnification of the instrument.

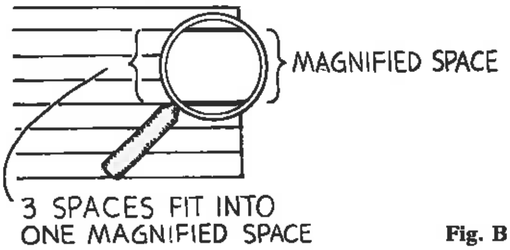


Fig. B

Think and Explain

1. a. What condition must exist for a converging lens to produce a virtual image?
   b. What condition must exist for a diverging lens to produce a real image?

2. How could you prove that an image was indeed a real image?

3. Why do you suppose that a magnifying glass has often been called a "burning glass"?

4. In terms of focal length, how far is the camera lens from the film when very distant objects are being photographed?

5. Can you photograph yourself in a mirror and focus the camera on both your image and the mirror frame? Explain.

6. If you take a photograph of your image in a plane mirror, how many meters away should you set your focus if you are 2 m in front of the mirror?

7. Copy the three drawings in Figure C. Then use ray diagrams to find the image of each arrow.

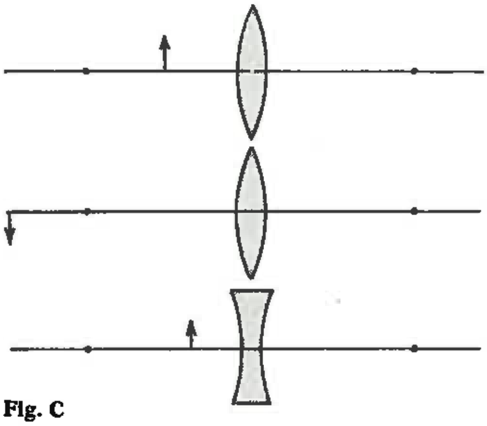


Fig. C

8. Why do you have to put slides into a slide projector upside down?

9. Maps of the moon are actually upside down. Why is this so?

10. What is responsible for the rainbow-colored fringe commonly seen at the edges of a spot of white light from the beam of a slide projector?

11. Why do older people who do not wear glasses read a book farther from their eyes than younger people?

12. Would telescopes and microscopes magnify if light had the same speed in glass as in air? Explain.