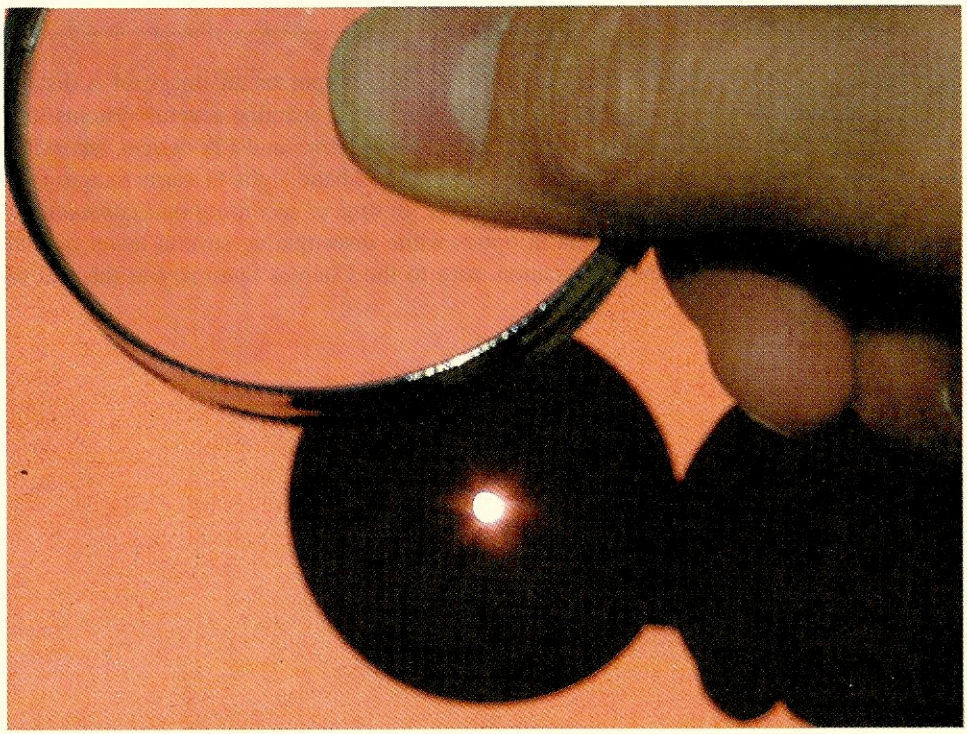
CHAPTER 15

Optics

Many of the devices around us perform useful tasks by manipulating light: cameras record images of the objects in front of them, our eyes allow us to observe those objects directly, and eyeglasses and magnifying glasses help us to see details we'd miss with our eyes alone. Still other gadgets, including CD and DVD players, use light in ways that have nothing to do with vision. However, all of these objects manipulate light using similar techniques—the techniques of optics.

Optical tools such as lenses and prisms have been around for hundreds of years, but advances of modern technology have accelerated the development of optics. Just as the invention of transistors has sped the growth of the electronics industry, so the invention of lasers has sped the growth of the optics industry. The two fields aren't far apart in many ways, and there is hope that one day computers will be as much optical devices as they are electronic.

EXPERIMENT: Focusing Sunlight



Courtesy Lou Bloomfield

There are many household devices that manipulate light, and one of the most familiar is a magnifying glass. A magnifying glass bends light rays toward one another as they pass through it. In this chapter, we'll see how a simple converging lens of this sort can magnify an object or cast its image onto a light-sensitive surface. For the moment, we'll simply use it to bring light rays together.

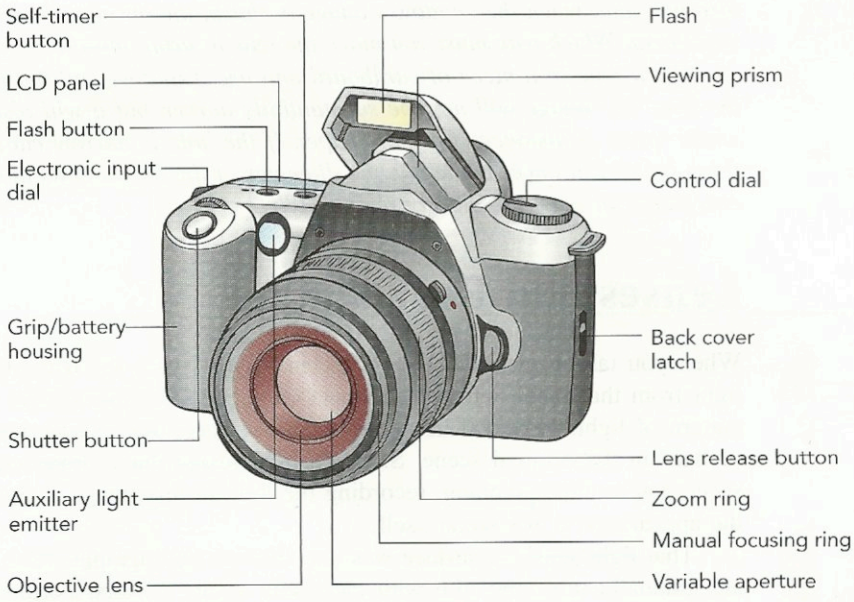
On a clear day with the sun roughly overhead, take a magnifying glass and a dark piece of paper outdoors to a place where there is nothing flammable around. You will use light from the sun to heat the paper until it smokes, so be prepared to extinguish a fire if necessary. Hold the magnifying glass just above the paper, and slowly lift the lens upward toward the sun. Make sure that the lens is turned so that its surface faces the sun. You should see a bright circle appear on the dark paper, and that circle should become smaller and smaller as you lift the lens. The sun's light rays are bending inward as they pass through the lens and are converging together as they head toward the paper. Be careful not to let this bright circle of light touch your skin because it will burn you. If the spot isn't round, try tilting the lens differently.

When the lens is just the right height above the paper, the circle of light will reach a minimum size. It will appear as a brilliant white disk that is actually an image of the sun itself. If the magnifying glass is wide enough and the sun is bright enough, the paper will begin to smoke. The image of the sun is then so bright that it is able to heat the paper to its ignition temperature. If the lens is quite large, the paper may begin to burn with a flame.

You can project images of other brightly illuminated objects on a sheet of white paper. What features of the lens determine the sizes of those images? What determines their orientations? Block part of the lens and see how it affects the images. Try to form images of objects at different distances from you. Do they all form images simultaneously, or do you have to adjust the lens somehow to bring each image into sharp focus?

Chapter Itinerary

This process of bringing light together to form a small spot or an image of a distant object is a common theme in optics. In this chapter, we'll examine several systems that are based on this sort of manipulation of light: (1) *cameras* and (2) *optical recording and communication*. In *cameras*, we'll see how lenses bend light to form images and how those images are used to create photographs. In *optical recording and communication*, we'll explore the roles of lasers in optics while investigating several novel optical effects. For additional preview information, turn to the Chapter Summary at the end of the chapter.



SECTION 15.1 Cameras

In the two centuries since their invention, cameras have become extremely easy to use. What started as a hobby for a few dedicated enthusiasts has evolved into an everyday activity. Despite all of the technological improvements, however, photography still employs many of the same principles it did in the 1800s. Cameras still use lenses to project images onto light-sensitive surfaces, and photographers still have to worry about getting the exposure right, focusing properly, and avoiding the blur of rapid motion. In this section, we'll explore some of the principles that make cameras work.

Questions to Think About: *Why are expensive camera lenses so complicated, with so many separate pieces of glass? Why does a longer lens seem to bring the objects nearer to you? What does a camera's aperture do? Why do nearsighted and farsighted people wear different eyeglasses?*

Experiments to Do: *The basic activity of a camera—projecting an image of the scene in front of you onto its image sensor—requires nothing more than a simple magnifying glass. In fact, you can use almost any simple lens that's bowed outward in the middle, including the eyeglasses of a farsighted person with no astigmatism or drugstore reading glasses. Stand in a darkened room, opposite a window. Hold a sheet of white paper so that it's parallel to the window, and move the lens back and forth in front of the paper. Make sure that the lens itself is parallel to the window.*

You should find a distance at which the lens casts a clear image of the window onto the sheet of paper. You'll find that the scene appears upside down and backwards and that the image becomes fuzzy if you move the lens toward or away from the paper. You'll

also find that, when the window's image is sharp, the outside scene's image is fuzzy and vice versa. Which way must you move the lens to bring more distant objects into focus?

Cut a hole in a piece of cardboard and use it to cover all but the center portion of the lens. The image will now be substantially darker, but it will also be sharper over a wider range of distances from the paper. If the hole is narrow enough, virtually everything focuses at once. Evidently, the diameter of the lens and its ability to focus on several things at once are closely related. Why?

Lenses and Real Images

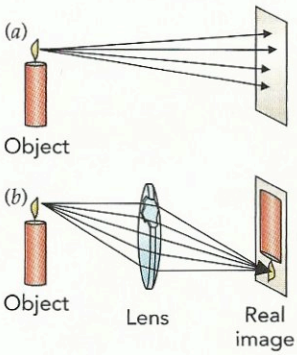


Fig. 15.1.1 (*a*) Without a lens, light from a candle uniformly illuminates an image sensor. (*b*) When a lens is introduced between the candle and the sensor, it brings light from each point on the candle back together on the sensor's surface, forming an upside down and backward real image of the candle. The distance between the lens and the sensor must be chosen correctly or the image will be blurry.

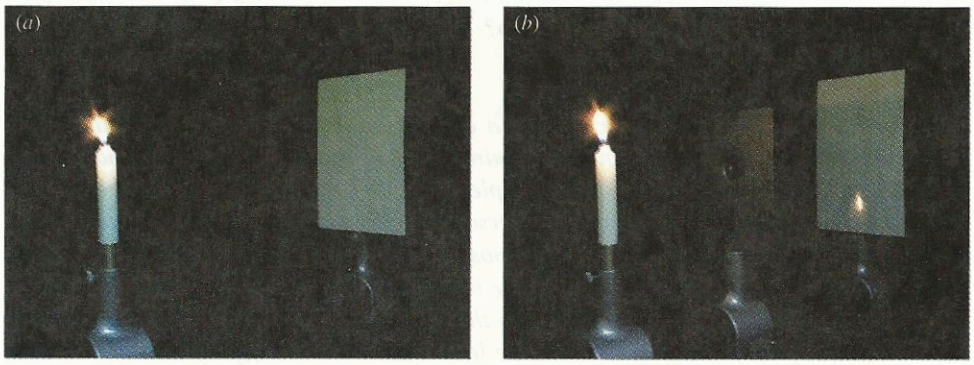
When you take a picture of the scene in front of you, the lens of your camera bends light from that scene into a real image on a light-sensitive surface. A **real image** is a pattern of light, projected in space or on a surface, that exactly reproduces the pattern of light in the original scene. Since the real image that's projected looks just like the scene you're photographing, recording the light in that image is equivalent to recording the appearance of the scene itself.

That light-sensitive surface was once always photographic film, but digital cameras are gradually replacing film with electronic image sensors. Fortunately, the two light-sensing surfaces are essentially interchangeable, so we can refer to them both as *image sensors*: one is electronic and one is photochemical.

Real images don't occur without help. When light from a candle falls directly on an image sensor, it produces only diffuse illumination (Fig. 15.1.1*a*). Similarly, you can't tell by looking at a sheet of paper what a candle looks like, because the light that leaves the candle travels in all directions and is as likely to hit the top of the paper as it is to hit the bottom (Fig. 15.1.1*b*).

That's why a camera needs a **lens**, a transparent object that uses refraction to form images. The light passing through a lens bends twice, once as it enters the glass or plastic and again as it leaves. In a camera lens, this bending process brings much of the light from one point on the candle back together at one point on the sensor. As you can see in Fig. 15.1.2, the real image that forms is upside down and backward. This inversion of the real image relative to the object always happens when a single lens creates a real image.

The curved shape of the camera lens allows it to form a real image. Light passing through the upper half of the lens is bent downward, while light passing through the lower half is bent upward. Because the camera lens bends light rays toward one another,



Courtesy Lou Bloomfield

Fig. 15.1.2 (*a*) When candlelight falls directly on a sheet of paper, it produces no image. (*b*) A lens inserted between the candle and paper forms an inverted real image of the flame on the paper.

it's a **converging lens**. You can see how it forms an image in Fig. 15.1.2*b* by following some of the rays of light leaving one point on the candle.

The upper ray from the candle flame travels horizontally toward the top of the lens. As it enters the lens and slows down, this ray of light bends downward. It bends downward again as it leaves the lens and travels downward toward the bottom of the image sensor.

The lower ray from the candle flame travels downward toward the bottom of the lens and bends upward as it enters the lens. It bends upward again as it leaves the lens and travels horizontally toward the bottom of the image sensor.

These two rays of light reach the image sensor at the same point. They are joined there by many other rays from the same part of the candle flame, so that a bright spot forms on the sensor. Overall, each part of the candle illuminates a particular spot on the image sensor, so the lens creates a complete image of the candle on the sensor.

However, the lens can bring the light back together to form a sharp image on the sensor only if the lens and sensor are separated by just the right distance (Fig. 15.1.3). If the sensor is too close to the lens, then the light doesn't have room to come together. If the sensor is too far from the lens, then the light begins to come apart again before reaching the sensor. In either case, the image on the sensor is blurry. The candle's real image is only *in focus* at one distance from the lens.

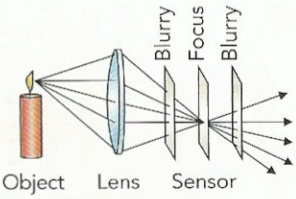


Fig. 15.1.3 The real image is in focus only when the image sensor is just the right distance from the lens. If the sensor is too near or too far from the lens, the image is blurry.

If the candle moves toward or away from the camera lens, the distance between the lens and the image sensor must also change (Fig. 15.1.4). When the candle is far away, all of its light rays that pass through the lens arrive traveling almost parallel to one another, and the inward bend caused by the lens makes those rays converge together quickly. The rays come into focus relatively near the lens, and that's where the sensor must be (Fig. 15.1.4*a*). The candle's image on the sensor is much smaller than the candle itself, because the light rays have only a short distance over which to move up or down after leaving the lens.

When the candle is nearby, its light rays that pass through the lens are diverging rapidly, and the inward bend caused by the lens is just barely enough to make those rays converge at all. As a result, the rays come into focus relatively far from the lens (Fig. 15.1.4*b*). The candle's image on the sensor is quite large because the light rays have considerable distance over which to move up or down after leaving the lens.

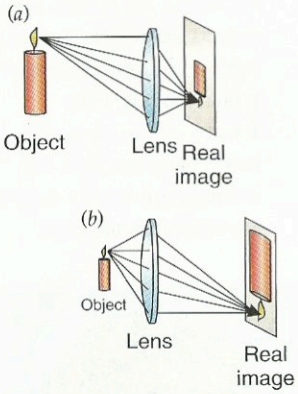


Fig. 15.1.4 (*a*) The light from a distant candle is traveling in almost the same direction and the lens focuses it easily. The real image forms close to the lens. (*b*) The light from a nearby candle diverges, and the lens has more difficulty bending it back together. The real image forms far from the lens. If the candle is too close to the lens, no real image forms at all.

Because distant and nearby objects form real images at different distances from the camera lens, they can't both be in focus on the same image sensor. When you take a picture of a person standing in front of a mountain, only one of them can be in sharp focus. However, if you're willing to compromise a little bit on sharpness, a lens can sometimes form acceptable images of both objects.

Check Your Understanding #1: Seeing the Lights

If you hold a magnifying glass at the proper distance above a sheet of white paper, you will see an image of the overhead room lights on the paper. Explain.

Answer: It is a real image of the room lights, created by the converging magnifying glass.

Why: A magnifying glass is a converging lens and can form a real image. It brings light spreading outward from the room lights together onto the sheet of paper as a real image.

Focusing and Lens Diameter

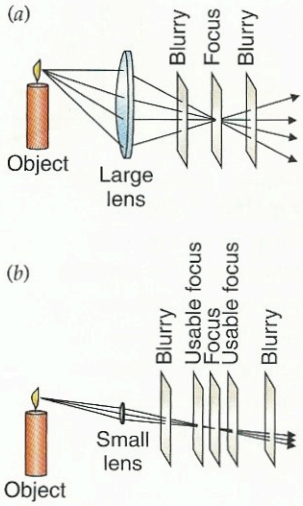


Fig. 15.1.5 (*a*) A large lens collects lots of light, but its focus is critical. The image is blurry except at the actual focus. (*b*) A small lens collects less light, but its image is relatively sharp anywhere near the focus.

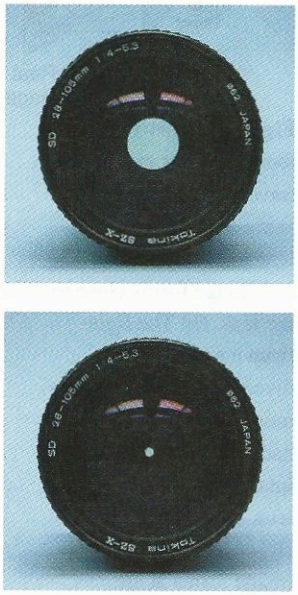
A disposable camera is little more than a box with a lens. The lens projects a real image of the scene in front of it onto the camera's image sensor. Light in the real image exposes the image sensor, which records the image permanently. While it may also have a shutter that starts and stops the exposure, a flash to provide extra light, and a mechanism that prepares for the next photograph, there's little else to this simple camera.

However, there are limitations to the disposable camera design. One of the most severe limitations is that you can't focus it—the camera has a fixed distance between the lens and image sensor. Nonetheless, it manages to form relatively sharp real images on the sensor, even when there are objects at various distances from the camera. These simple cameras work because they use narrow (small-diameter) lenses. A narrow lens gathers less light than a wide lens but doesn't require *focusing*—adjusting the distance between the lens and the image sensor.

Because a wide (large-diameter) lens brings rays together from many different directions, you must focus it (Fig. 15.1.5*a*); if the image sensor is even slightly too near or too far from the lens, the recorded image will be blurry. A narrow lens forms a reasonably clear image even without focusing. Any rays from one part of the scene that succeed in passing through the narrow lens must already be fairly close together. Their initial closeness means that these converging rays illuminate only a small part of the image sensor even when the sensor isn't exactly the right distance from the lens (Fig. 15.1.5*b*). Since the image sensor can't record every minute detail anyway, the image that forms on it doesn't have to be in absolutely perfect focus. As a result, a camera with a narrow lens and no focus adjustment manages to take pretty good pictures.

Unfortunately, these simple cameras collect very little light and need extremely light-sensitive image sensors. These high-speed sensors can't record photographs as sharp as low-speed sensors can. Furthermore, the pictures produced by simple cameras lack fine details; although everything is almost in focus, most things are a bit fuzzy if you look carefully or make enlargements.

More sophisticated cameras use wider lenses that gather more light and expose the image sensors much more rapidly. They also automatically adjust the distance between the lens and the sensor. They identify the object you are photographing and position the camera lens so that it projects a sharp image on the sensor. As the camera focuses, you can usually see components in the lens moving backward or forward to arrive at the correct distance from the sensor.



Courtesy Lou Bloomfield

Fig. 15.1.6 The aperture of this lens can be reduced by closing its internal diaphragm, dimming its image but increasing its depth of focus.

Even a camera with a wide lens can take advantage of the narrow lens trick for focusing. Its lens contains an internal diaphragm that reduces its **aperture** or effective diameter. The *diaphragm* is a ring of metal strips with a central opening. These strips can swing in or out, changing the diameter of the diaphragm's opening and with it the aperture of the lens (Fig. 15.1.6).

When its lens aperture is narrow, the sophisticated camera imitates a simple camera. Nearly everything is essentially in focus simultaneously. In such a situation, the camera has a large *depth of focus*. Actually, the sophisticated camera can bring the most important object into perfect focus, so it produces pictures that are superior to those from simple cameras. However, narrowing the aperture of the lens also reduces the amount of light reaching the image sensor. The scene in front of the camera must either be very bright or the exposure must be relatively long. You don't get something for nothing.

Although widening the aperture of a large lens makes full use of its light-gathering capacity, focusing then becomes crucial. Even a small error in the lens-to-sensor distance produces a blurry picture, so the depth of focus is very small. This trade-off, between

light gathering and depth of focus, is a continual struggle for photographers. However, photographers sometimes take advantage of the small depth of focus in wide lenses to blur the background or foreground of a photograph deliberately. A camera's portrait setting adopts this strategy to produce sharp images of people against blurred backgrounds.

At other times, photographers choose long exposures at narrow apertures in order to bring an entire scene into sharp focus. A camera's landscape setting takes this route, so that everything in the photograph shows full detail. To capture fast motion while retaining a large depth of focus, photographers use a flash to brighten the scene and shorten the exposure. Unfortunately, a camera flash is ineffective at brightening a distant scene, and it can produce unpleasant reflections from windows and eyes. A camera's sports setting emphasizes brief exposures to avoid speed blur, even though that may require a wide aperture and small depth of focus.

Check Your Understanding #2: Portrait Photos

While taking a photograph of your friend, with the diaphragm of your large camera lens wide open, you notice that the background is blurry. Explain.

Answer: Light from the more distant background focuses closer to the lens than light from your friend. Since the camera is focusing on your friend, the background appears out of focus.

Why: When the aperture of your camera lens is wide open, focusing becomes critical. Objects in front of or behind your friend are out of focus on the image sensor and appear blurry.

Focal Lengths and f-Numbers

Lenses are characterized by two quantities: focal length and f-number. The **focal length** of a lens is the distance between the lens and the real image it forms *of a very distant object*. For example, if a real image of the moon forms 100 mm (4 in) behind a particular lens, then that lens has a focal length of 100 mm. The focal lengths of camera lenses range from less than 10 mm (0.4 in) in many compact cameras to about 2 m (7 ft) in cameras used for nature photography.

When light from a scene passes through a short focal length lens, it comes to a focus near that lens and produces a relatively small image on the image sensor. Because a long focal length lens permits the light passing through it to spread out more before coming to a focus, it produces a larger real image on the sensor.

The "normal" lens for a particular camera has a focal length that allows all of the objects in your central field of vision to fit onto the image sensor (see Table 15.1.1).

Table 15.1.1 Several Cameras, the Widths of the Image Sensor They Use, and Their Normal Lenses

TYPE OF CAMERA	SENSOR WIDTH	NORMAL LENS
Typical digital camera	8 mm	12 mm
35-mm camera	36 mm	50 mm
2¼-inch medium format camera	2¼ inches	80 mm
5-inch portrait camera	5 inches	180 mm

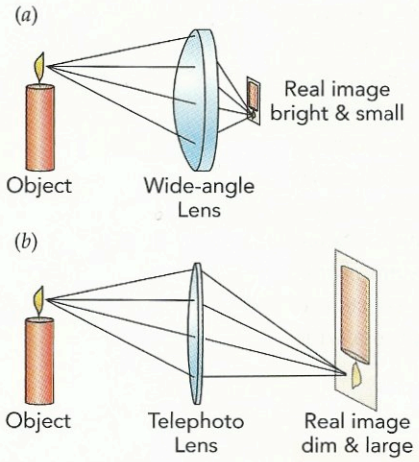


Fig. 15.1.7 (*a*) A wide-angle lens has a short focal length and forms a small, bright real image near the lens. (*b*) A telephoto lens has a long focal length and forms a large, dim real image far from the lens.

When you hold the finished photograph about 30 cm (1 ft) from your eyes, the objects in the picture appear about the same size they did when the photograph was taken. The focal length of a camera's normal lens is about 1.5 times the horizontal width of its image sensor.

A wide-angle lens has a shorter focal length than the normal lens (Fig. 15.1.7*a*). The image it projects onto the image sensor is smaller but brighter, and most of the objects in your entire field of vision appear in the photograph. A telephoto lens has a longer focal length than the normal lens (Fig. 15.1.7*b*). The image it projects onto the sensor is larger but dimmer, with only objects at the center of the scene appearing in the photograph.

In addition to indicating where the image of a distant object forms, the focal length of the camera lens relates the object distance to the image distance. The **object distance** is the distance between the lens and the object you're photographing. The **image distance** is the distance between the lens and the real image it forms (Fig. 15.1.8). The relationship is called the **lens equation** and can be written in a word equation:

$$\frac{1}{\text{focal length}} = \frac{1}{\text{object distance}} + \frac{1}{\text{image distance}}, \tag{15.1.1}$$

in symbols:

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

and in everyday language:

The farther away an object is, the closer to the lens its image forms.

The Lens Equation

One divided by the focal length of a lens is equal to the sum of one divided by the object distance and one divided by the image distance.

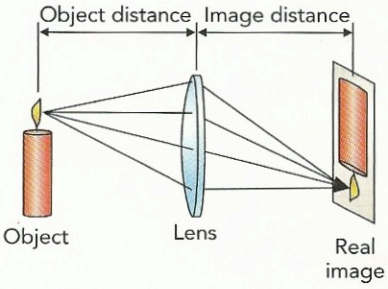


Fig. 15.1.8 The relationship between the object distance, the image distance, and the focal length of the lens is given by the lens equation.

According to the lens equation, the image distance for a distant object is equal to the focal length of the lens. That agrees with our earlier discussion of focal length. However, when the object is nearby, the image distance becomes larger than the focal length. That's why a camera lens moves away from the image sensor as you focus closer. When the object distance becomes less than the focal length, the image distance becomes negative and no real image forms at all. That's why you can't focus on an object that's too close to the lens.

A lens's **f-number** characterizes the brightness of the real image it forms on the image sensor, with smaller f-numbers indicating brighter images. The f-number is calculated by dividing the lens's focal length by its diameter, or

$$\text{f-number} = \frac{\text{focal length}}{\text{diameter}}.$$

Since long focal length lenses naturally produce larger and dimmer images on the image sensor, the f-number takes into account both the light-gathering capacity of the lens and its focal length. Increasing a lens's diameter increases its light-gathering capacity and decreases its f-number. Increasing a lens's focal length decreases the brightness of its real image and increases the f-number. Doing both at once, increasing the lens diameter and focal length equally, leaves the brightness and f-number unchanged.

Most sophisticated cameras use large-diameter lenses so that their f-numbers are generally less than 4. Since it's difficult to fabricate a lens that's larger in diameter than its focal length, the smallest practical f-number is about 1. Also, because long focal length lenses need large apertures to keep their f-numbers small, some telephoto lenses are huge.

The diaphragm inside a lens allows you to decrease the lens's aperture and thus increase its f-number. A factor of 2 increase in f-number corresponds to a factor of 2 decrease in the lens's effective diameter and a factor of 4 decrease in the lens's light-gathering area. Thus when you double the f-number of the lens, you must compensate by quadrupling the exposure time. Although closing the aperture increases the lens's depth of focus, it requires a longer exposure.

Check Your Understanding #3: **Bright and Sharp Photographs**

On bright, sunny days, your automatic camera takes photographs with large depths of focus, while on dark, overcast days its pictures have much smaller depths of focus. What causes this difference?

Answer: On a bright day, your camera needs only a small aperture to gather enough light for an exposure, so the depth of focus is large. On a dark day, it uses the largest aperture available to gather light and has a small depth of focus.

Why: Light gathering and depth of focus go hand in hand. If you must open the aperture of your camera's lens to gather enough light for an exposure, focusing will become critical and your photographs will have small depths of focus.

Check Your Figures #1: **The Image of an Apple**

If the distance from an apple to a converging lens is twice the focal length of that lens, where will the real image of the apple form?

Answer: The image will form at a distance twice the focal length behind the lens.

Why: Since the object distance is twice the focal length, we can use Eq. 15.1.1 to find the image distance:

$$\begin{aligned}\frac{1}{\text{image distance}} &= \frac{1}{\text{focal length}} - \frac{1}{\text{object distance}} \\ &= \frac{1}{\text{focal length}} - \frac{1}{2 \cdot \text{focal length}} \\ &= \frac{1}{2 \cdot \text{focal length}}.\end{aligned}$$

The image distance is twice the focal length of the lens.

Improving the Quality of a Camera Lens

A high-quality camera lens isn't a single piece of glass or plastic. Instead, it's composed of many separate elements that function together as a single lens. This complexity improves the quality of the real image. To begin with, dispersion in a single-element lens causes different colors of light to bend differently and focus at different distances behind that lens. Known as *chromatic aberration*, this problem can be fixed by using several lens elements made of different types of glass, with different amounts of dispersion. These elements compensate for one another so that the overall lens, known as an *achromat*, has very little dispersion and almost no color-focusing problems.

After correcting for color and other technical image problems, a sophisticated camera lens may contain more than ten individual elements. For the purposes of the lens equation, this complicated lens has an effective center from which to calculate object and image distances. However, having so many separate elements creates reflection problems; each time light passes from air to glass or vice versa, some of it reflects. To avoid fogging the photographs with this bouncing stray light, the individual elements are *antireflection coated* with thin layers of transparent materials. The best coatings use interference effects to cancel out the reflected light waves and give the lens only a weak violet reflection.

Many modern cameras are equipped with zoom lenses. A zoom lens is a complicated lens that can change the size of the real image it projects onto the image sensor. By carefully moving its lens elements relative to one another, the zoom lens can adjust its effective focal length.

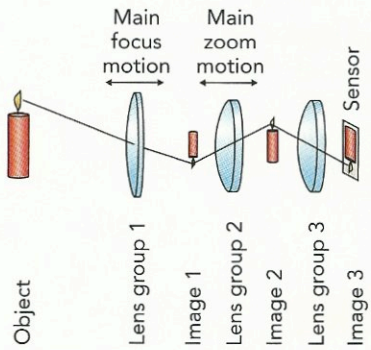


Fig. 15.1.9 A common type of zoom lens uses three lens groups to project a variable-size real image on the image sensor. Zooming is done mostly by moving the second lens group to change its image and object distances. The first lens group is responsible for focusing, and the third lens group projects the real image on the sensor.

A common type of zoom lens contains three separate groups of lens elements and produces a sequence of three images (Fig. 15.1.9). The first lens group forms a first image of the scene in front of the camera. The second lens group forms a second image of that first image. The third lens group projects a third, real image of the second image onto the image sensor. Zooming the lens—that is, changing its focal length—involves altering the spacings between the lens groups in order to vary the second lens group's object and image distances and thus the relative sizes of the first and second images.

As the zoom lens changes from short focal length to long focal length, the image it projects on the sensor becomes larger. This effect allows you to compose the picture so that the scene fills the photograph completely. A lens that can change its focal length while retaining the same f-number and still keep the real image in focus on the sensor is a truly remarkable achievement.

Check Your Understanding #4: Not Such a Good Picture

If you use a large magnifying glass to form a real image of an overhead fluorescent light fixture, you will find that the corners of the light fixture are blurry and have rainbow colors in them. Why is the image quality so poor?

Answer: The magnifying glass has only one glass element and suffers from chromatic aberration (and many other image imperfections).

Why: A single converging lens can't form a high-quality image on a flat surface because it has chromatic aberration, spherical aberration, coma, and astigmatism. If the lens is small, these failings are often invisible. In a large magnifying glass, however, they are all readily apparent and you can't form a sharp image of the entire light fixture.

The Viewfinder and Virtual Images

SLR or single lens reflex cameras permit you to change their lenses so that you can choose a lens that's optimized for the task at hand. When you peer through the viewfinder of an SLR camera (Fig. 15.1.10), you're looking at the same real image that will be projected onto the image sensor during the exposure. The light you see travels through the camera's main lens, reflects off a mirror, and projects onto a translucent screen inside the top of the camera. You're simply inspecting this screen and the real image through a magnifying lens in the eyepiece. During the exposure, the mirror flips out of the way and the real image projects briefly onto the image sensor.

Courtesy Lou Bloomfield

Fig. 15.1.10 The mirror in the center of this reflex camera directs light from the lens (removed for this photograph) onto the focusing screen above it. During the exposure, the mirror swings upward to permit light from the lens to strike the image sensor at the back of the camera.

Since the screen and real image are only an inch or two from your eye, you can't focus on them without the help of the eyepiece lens. The eyepiece lens is converging, but in this case it doesn't form a real image. Instead, it forms a **virtual image**—an image located at a negative image distance—that is, on the wrong side of the lens!

The screen displaying the scene that you're photographing is so close to the eyepiece lens that the object distance is less than that lens's focal length. According to the lens equation, the image distance should be negative and it is; the image is located on the screen side of the eyepiece lens (Fig. 15.1.11). You can't put your fingers in the light and project this image on your skin because the image is virtual rather than real.

You can, however, see this image through the eyepiece. It's located farther away than the screen itself, so your eye can comfortably focus on it. Also, the image is magnified—the eyepiece lens is acting as a magnifying glass (Fig. 15.1.12). This lens provides magnification because when you look at the screen through it, the screen image covers a wider portion of your field of vision. This magnification increases as the eyepiece lens's focal length decreases. That's because a shorter focal length eyepiece lens must be quite close to the screen, where it can bend light rays coming from a smaller region so that they fill your field of vision. The eyepiece lens in a typical camera has been chosen so that the screen fills a comfortable portion of your visual field, allowing you to examine the virtual image in great detail and adjust the lens and camera settings until you have just the right picture in your view. Then all you have to do is take the photograph.

Cameras with fixed lenses often have two separate viewfinder systems. A typical digital camera has a small electronic viewfinder, which displays the real image being projected onto its image sensor. Many digital and all film cameras also have optical viewfinders. Although optical viewfinders vary in style and sophistication, the best combine real and virtual images. In a *real-image optical viewfinder*, a system of lenses, mirrors, and/or prisms produces an erect real image of the scene, and you then examine that

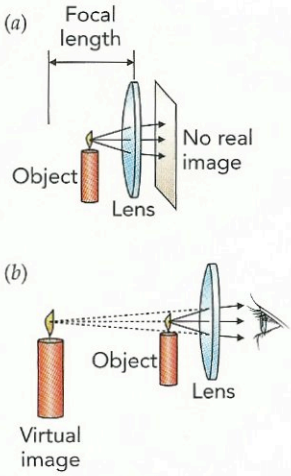
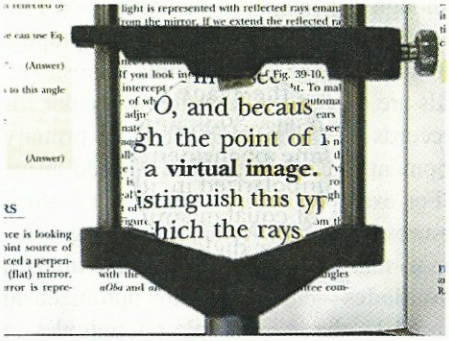


Fig. 15.1.11 (*a*) Light from an object very near a converging lens diverges after passing through the lens, and no real image forms. (*b*) Your eye sees a virtual image that is large and far away.



Courtesy Lou Bloomfield

Fig. 15.1.12 This magnifying glass creates an enlarged virtual image located far behind the printed text. You can't touch the image or put your fingers in its light, but you can see it clearly with your eyes.

real image through an eyepiece magnifying glass. The lenses projecting the real image zoom along with the camera's main lens so that what you see through the viewfinder is similar to what the camera's image sensor will record.

Check Your Understanding #5: Real and Virtual Images

As you move a magnifying glass slowly toward the photograph in front of you, you see an inverted image that grows larger and nearer to your eye. This image eventually becomes blurry, and then a new upright and enlarged image appears on the photograph's side of the lens. What's happening?

Answer: The lens is initially creating a real image near your eye. This real image moves past you as the lens approaches the photograph. Finally, the lens is close enough to create an enlarged virtual image of the photograph.

Why: A magnifying glass forms either a real or virtual image, depending on object distance and the lens's focal length. If the lens and photograph are separated by more than the focal length, the image is real and you see it near your eye. You can touch this inverted image or project it on a piece of paper. If the lens and picture are separated by less than the focal length, the upright image is virtual and you see it on the far side of the lens.

Image Sensors

Once the lens has projected its real image onto the image sensor, it's the image sensor's job to record that pattern of light. Interestingly enough, both film and electronic image sensors use semiconductors and both detect light when its photons shift electrons from valence levels to conduction levels. However, how those two image sensors act on the electron transitions is quite different.

Photographic film detects light photochemically. Embedded in the film are tiny crystals of silver salts. Composed primarily of silver and halogen atoms, these semiconductor crystals are extremely sensitive to light. When a silver halide crystal absorbs a photon of visible light, it can undergo a radiative transition that shifts an electron from a valence level to a conduction level and eventually frees one silver atom from a silver halide molecule. After several nearby silver atoms have been freed by light, they can form a tiny particle of silver metal. When the film is developed, this silver particle transforms the entire silver halide crystal into metallic silver. The microscopically rough structure of that silver makes it appear black rather than shiny.

In black-and-white photography, the silver particles themselves form a negative image on the developed film. Wherever the film was struck by light, it acquires a dense, black pattern of silver particles. Wherever light was absent, the film becomes clear once the unexposed silver salts are washed away. Although the image on the developed film itself is negative—light is dark and dark is light—the process of preparing photographic prints reverses light and dark a second time so that the image on the prints is positive.

In color photography, the silver halide crystals are exposed to light through color filters and sensitizers, so that the film separately records its exposure to the three primary colors of light (see Section 14.2). During development, the silver itself is washed away, but a negative color image remains in the film. For example, wherever blue light struck the film, it acquires a yellow tint and therefore absorbs blue light. Again, the photographic printing process reverses the colors a second time so that the prints have positive images.

Electronic image sensors are based on **photodiodes**—diodes that are optimized to detect light. Like tiny photovoltaic cells (Section 14.1), the microscopic photodiodes in

an image sensor separate positive and negative electric charges when exposed to light. A vast array of these photodiodes record the pattern of light in the real image and the camera subsequently reads that pattern by measuring the accumulated charges on each of its photodiodes. To obtain color information, the image sensor's photodiodes are covered with a pattern of red, green, and blue filters so that each photodiode measures the intensity of only one primary color of light.

Check Your Understanding #6: Foggy Photos

Airport screening devices often use X-rays to search for hidden items. These high-energy photons can damage film. How?

Answer: X-rays cause radiative transitions in the silver salt crystals.

Why: X-rays can penetrate through normally opaque objects and reach the film. If a silver salt crystal in the film absorbs an X-ray, it will respond as though it was exposed to visible light. Although most modern screening devices use such weak X-ray sources that the effects are minimal, repeated screenings of high-speed film will gradually ruin it.

Eyes and Eyeglasses

Not all cameras involve modern technology. Most people are born with two of them: their eyes. Like the cameras we discussed above, each eye consists primarily of a converging lens and an image sensor (Fig. 15.1.13). In this case, the lens is a combination of the front surface of the eyeball, its *cornea*, and the internal lens just beneath the cornea. The image sensor is the retina, a vast pattern of light-sensitive cells and nerves at the back of the eyeball.

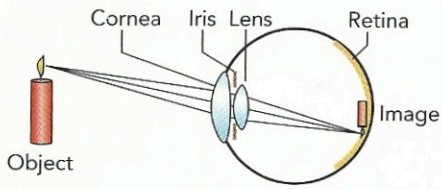


Fig. 15.1.13 An eye is a camera, with its cornea and lens forming a real image on the retina. The eye focuses by changing the curvature of its lens. The iris changes the eye's f-number.

When you look at the scene in front of you, the cornea and lens of your eye project a real image of that scene onto your retina and your retina reports the resulting pattern of light to your brain. As usual, the real image is inverted and reversed left to right, but your brain compensates for that effect.

Since your eyeball can't alter the distance between the lens and the image sensor, it focuses the real image by adjusting the focal length of the lens. When you look at nearer objects, the lens in your eye becomes more highly curved and its focal length decreases. The light rays from that nearer object thus converge more sharply and form a real image on your retina. When you view a more distant object, the lens becomes less curved and its focal length increases.

Like a sophisticated camera, your eye has an iris within its lens system. When you view a bright scene, that iris shrinks to limit the amount of light striking your retina. As a side effect, your depth of focus increases and everything appears sharper. It's easier to focus when you read or work in a well-lighted environment.

However, not all eyes are perfect, and many need help forming sharp real images on their retina. Although modern laser surgical techniques can reshape corneas to improve image sharpness, the classic approach to better vision is to wear eyeglasses or contact lenses. An eye's lens system already consists of two components, the cornea and the lens, so adding a third component, eyeglasses, is no big deal.

A person who is farsighted can't see nearby objects sharply because her lens system has too long a focal length (Fig. 15.1.14*a*). Although it can project real images of

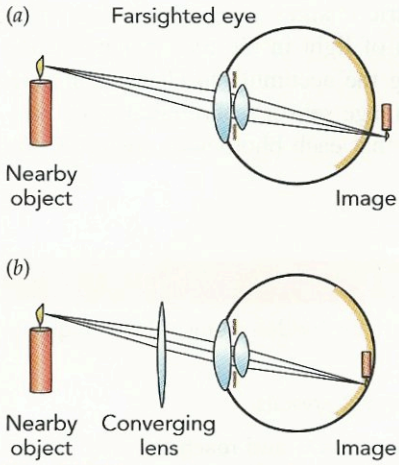


Fig. 15.1.14 (*a*) A farsighted eye bends light too weakly to focus on a nearby object. The real image forms beyond the retina. (*b*) A converging lens shifts the real image forward so that it focuses on the retina.

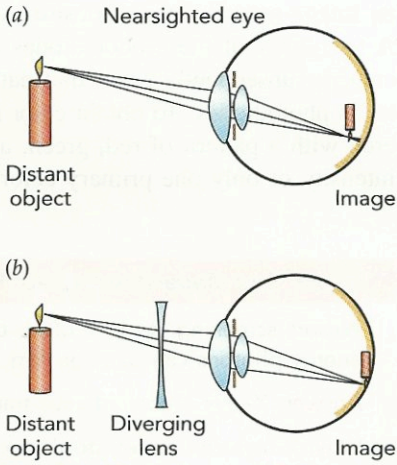


Fig. 15.1.15 (*a*) A nearsighted eye bends light too strongly to focus on a distant object. The real image forms before the retina. (*b*) A diverging lens shifts the real image backward so that it focuses on the retina.

distant objects on her retina, nearby objects focus too far away from the front of her eye, and the light strikes her retina before it forms a real image.

To compensate for farsightedness, she wears eyeglasses with converging lenses (Fig. 15.1.14*b*). These lenses begin the task of bending light rays together even before they enter her eyes. Her own lens system completes the bending, and the real images form closer to the front of her eyes. She is thus able to see distant objects clearly.

In contrast, a person who is nearsighted is unable to focus on distant objects because his lens system has too short a focal length (Fig. 15.1.15*a*). Real images of those distant objects form too close to the front of his eye, and the light has already begun to spread apart by the time it reaches his retina.

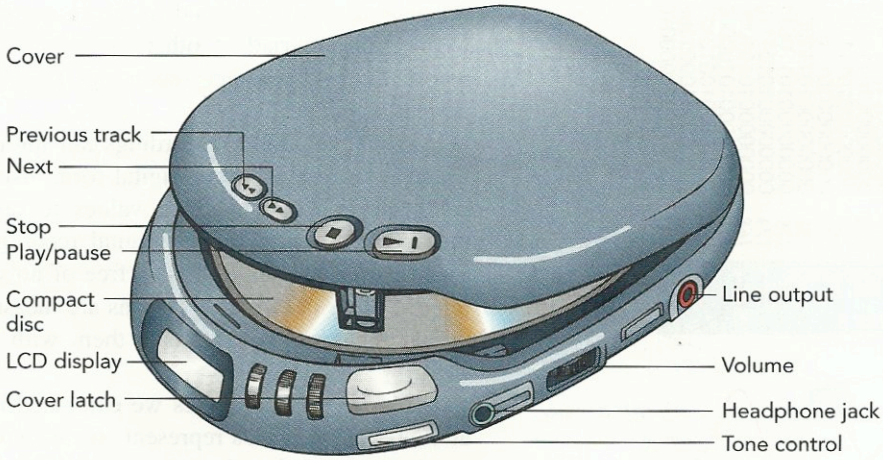
To compensate for nearsightedness, he wears eyeglasses with diverging lenses (Fig. 15.1.15*b*). A **diverging lens** is one that bends light rays apart and therefore has a negative focal length. Typically thinner at its middle than at its edge, a diverging lens bends the nearly parallel rays of light from a distant object so that they diverge more rapidly. Those rays then appear to come from a much nearer object, actually a nearby virtual image, and his eyes are able to focus them properly on his retina.

Check Your Understanding #7: Keeping Up Your Image

The eyeglasses of a farsighted person can project a real image of a distant scene on a white wall. However, the eyeglasses of a nearsighted person produce no real image. Why not?

Answer: Nearsighted eyeglasses use diverging lenses, which bend light rays apart and don't focus them together into a real image.

Why: To form a real image of a distant scene, you need to bring light rays together with a converging lens. Diverging lenses spread light rays apart and can't form real images on their own.



SECTION 15.2 Optical Recording and Communication

Using light to convey information is as old as signal fires and as natural as sight itself. Over the years, advances in light sources, optical materials, and electronics have radically increased the possibilities for optical information systems. Optics and information go so well together that they're partly responsible for the current information revolution. The introduction of compact disc players in the early 1980s transformed the music industry virtually overnight, and optical fibers are knitting our world together at an astonishing pace. In this section, we'll look at how optical devices use light to manipulate information.

Questions to Think About: *Where is a CD or DVD's information stored? How can CD or DVD players ignore fingerprints, dust, and other surface contamination during playback? Why is a laser involved in recording and playing back a CD or DVD? Why can a Blu-ray disc hold more information than a DVD and a DVD more than a CD? Why are CDs and DVDs so free of noise? How can a glass fiber direct light in a curving path? How can light travel through kilometers of glass fiber without becoming dim?*

Experiments to Do: *Hold a prerecorded CD or DVD by its edges and look at its unlabeled surface. Beneath the clear plastic face is a smooth, shiny layer that reflects a rainbow of colors. Tiny pits in this layer cause this coloration. These pits form a spiral track around the center of the disc, and adjacent arcs of this track are so closely spaced that light waves reflecting from them interfere, as from a soap film. The reflective layer is so thin that you can see through it if you hold it in front of a bright light. Can you see the reflections of dust particles on the unlabeled surface? How deep below the plastic surface is the shiny layer?*

Digital Recording

Although analog techniques dominated audio recording for about a century, they were replaced by digital techniques in less than a generation. It was mostly a matter of sound quality. Analog recording, in which a continuous physical quantity represents the density

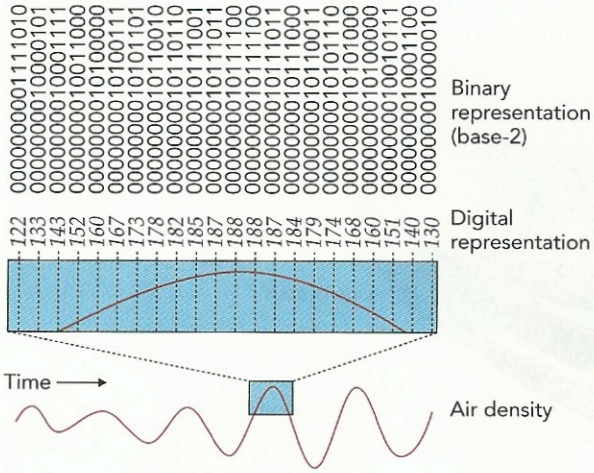


Fig. 15.2.1 Sound can be represented as a series of numbers. Each number corresponds to the air density at a particular moment in time.

fluctuations that are sound in air, is susceptible to noise, wear, and a myriad of other imperfections. Phonograph records and analog tape recordings simply can't provide perfect sound.

In contrast, digital recordings can approach perfection. By representing sound in digital form, using many physical quantities with discrete values to represent density measurements numerically, digital recording can provide exact sound information that's free of noise and wear. As long as those density fluctuations are measured accurately, digital recording can recreate them with uncanny precision.

Like the audio players we examined in Section 12.2, audio CDs and DVDs represent sound's compressions and rarefactions of the air as numbers (Fig. 15.2.1). These numbers are essentially air density measurements taken over and over again during the recording process, and the player uses them to reproduce the recorded sound.

In the conventional CD format, density measurements are made 44,100 times each second for two independent audio channels, and these measurements are recorded on the disc in binary form, using 16 bits for each measurement. Since the air density can go down as well as up, these bits represent the positive and negative integers from $-32{,}768$ to 32,767, which in turn represent how much the air density is above or below the average density. Density measurements with 16 bits of precision are sufficient to reproduce both loud and soft music with almost perfect fidelity.

Like CDs, DVDs record information digitally, but DVDs are newer technology and therefore more sophisticated. Audio DVDs can choose from several measurement rates, bits per measurement, and numbers of channels. A typical DVD might have five audio channels: left-front, center-front, right-front, left-rear, and right-rear. The three front channels might have 96,000 density measurements per second at 24 bits per measurement, and the two rear channels might have 48,000 measurements per second at 20 bits per measurement. All of these samples, bits, and channels involve far more information than is stored on a CD, and a DVD compresses that information before storing it. In contrast, a conventional CD's information is uncompressed, although some more modern formats (e.g., mp3) do employ compression techniques.

In either case, air density measurements aren't simply recorded one after another on a disc's surface. Instead, these numbers are extensively reorganized before they're stored. This reorganization allows the player to reproduce the sound perfectly even if the disc can't be read completely. As we'll see shortly, reading these discs is a technological tour de force and susceptible to various failures. To be sure that the sound (and video) can be reproduced completely and without interruption, the numbers are recorded in an encoded manner. They appear redundantly so that even if one copy of a number is illegible, there is still enough legible information along the same arc of the disc's spiral track to completely recreate that missing number. This duplication of information reduces the playing time of both CDs and DVDs but is essential for reliability.

Its encoding scheme leaves a CD or DVD almost completely immune to all but the most severe playback problems. In principle, you can damage or obscure a 2-mm-wide swath of the disc, from its center to its edge, and the player will still be able to reproduce the sound (and video) perfectly. However, damage along an arc of the spiral track is far more threatening to the data. If the player can't read a long stretch of a single arc, it won't be able to recover the information. That's why you should always clean a CD or DVD from its center outward to its edge.

Check Your Understanding #1: Cordless Clarity Away from Home

Cell phones transmit your voice in digital form. In general terms, how does this digital transmission work?

Answer: Your cell phone's microphone converts the sound of your voice into a fluctuating current. This current is measured periodically and represented as a sequence of numbers. These numbers are then represented by radio waves and transmitted through space. The numbers eventually work their way to a receiving cell phone, where the radio waves are converted back into numbers and the numbers are converted back into a fluctuating current. Finally, the current is amplified and sent through a speaker to create sound.

Why: Many modern communication devices use a digital representation of sound. In radio wave communication, digital representations are particularly useful because they are immune to the noise that plagues analog radio transmissions and also permit more efficient use of the radio bandwidth.

The Structure of CDs and DVDs

Standard CDs and DVDs are 120 mm (4.72 inches) in diameter and 1.2 mm (0.05 inches) thick. One side of a CD is clear and smooth but the other side contains a sandwich of layers: a thin film of aluminum, a protective lacquer, and a printed label (Fig. 15.2.2*a*). In contrast, a DVD is laminated from two 0.6-mm-thick clear plastic discs, with one, two, or four reflective layers of aluminum, gold, or silicon stacked up in between them (Fig. 15.2.2*c*). The more layers in the DVD, the more information it holds.

The reflective layers are the recording surfaces. These layers are so thin that they actually transmit a small amount of light. In the gold or silicon DVD layers, this semitransparency is essential because it allows the optical system that reads information to send light through the semitransparent layer to the aluminum layer beyond it. The aluminum layers also transmit some light. Although aluminum's electrons accelerate in response to the light's electric field and normally reflect that light completely, there aren't enough electrons in these 50- to 100-nm-thick layers to do the job and some light gets through.

The reflective layers aren't perfectly smooth. Instead, each has a narrow spiral track formed in its surface (Figs. 15.2.2*b,d*). This track is a series of microscopic pits, as little as 0.83 μm long on a CD or 0.40 μm long on a DVD. Adjacent arcs in the spiral track are only 1.6 μm apart on a CD and just 0.74 μm apart on a DVD. The lengths of the pits and the flat "lands" that separate them represent numbers. The player examines these pits and lands as the disc turns and converts their lengths into numbers, sound, and video.

The pit lengths and the spacings between arcs weren't chosen arbitrarily. Since electromagnetic waves are unable to detect structures much smaller than their wavelengths (see Section 13.2), the laser beam's wavelength limits the smallest features on a disc. In a CD player, that beam's wavelength is 780 nm in air and 503 nm in polycarbonate plastic—short enough to detect the pits of a CD easily. In a DVD player, the laser beam's wavelength is between 635 and 650 nm in air and between 410 and 420 nm in plastic—just short enough to detect the pits in a DVD. The wavelength reduction inside the disc occurs because polycarbonate plastic has an index of refraction of 1.55, meaning that the light's speed in that plastic is reduced from its vacuum speed by a factor of 1.55. Its wavelength is reduced by the same factor.

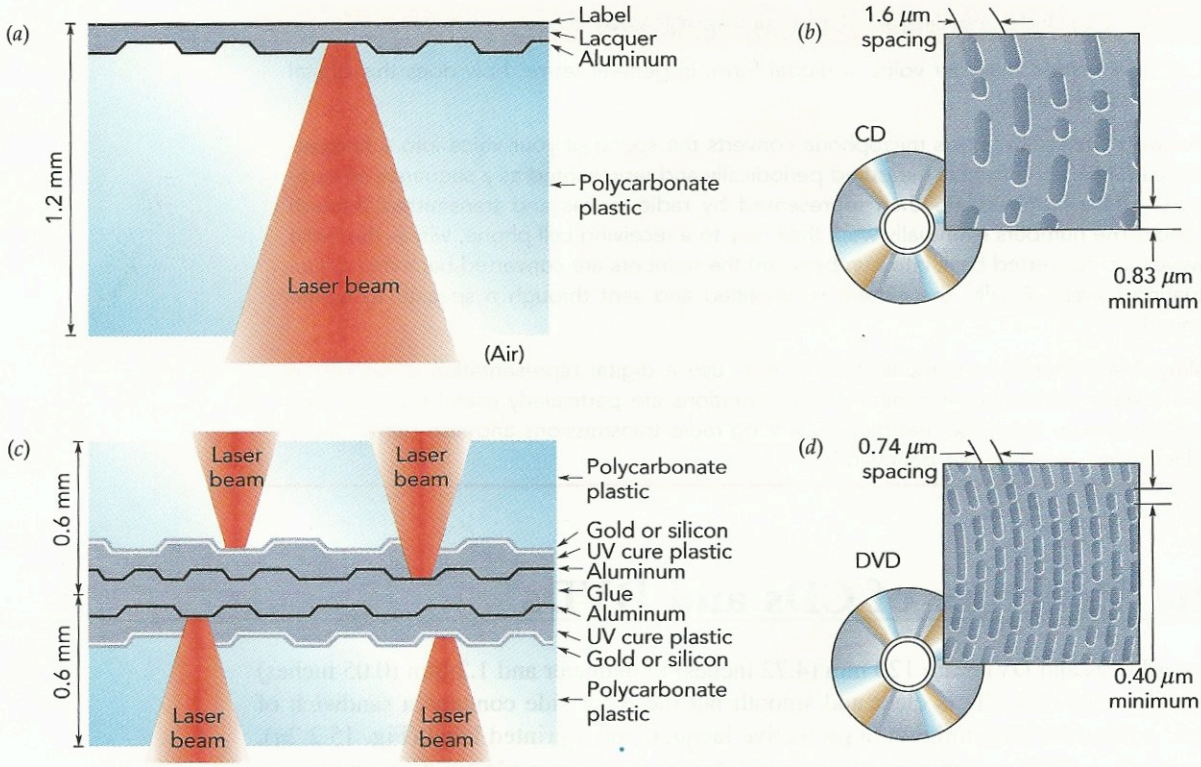


Fig. 15.2.2 (*a,b*) A CD contains a thin layer of aluminum on one side of a clear plastic disc. The aluminum layer has tiny pits that are detected by a 780-nm laser beam. (*c,d*) A DVD contains up to four aluminum, gold, or silicon layers sandwiched between two clear plastic discs. The gold or silicon layers are semireflective. Pits in those layers are detected by a 650-nm laser beam. The beam can focus either on the semireflective layer or, by passing through that layer, on the aluminum layer beyond it.

The player detects a pit by bouncing light from the disc and determining how much of it reflects. As the focused laser beam passes over a pit, the reflection becomes dim, in part because the curved pit scatters light in all directions and in part because of interference effects. Light that's reflected back from a pit travels farther than light that's reflected from the flat region around it, so electric and magnetic fields in the two waves are shifted relative to one another. The pit depth was chosen so that the two reflected waves are approximately out of phase and they interfere destructively. Overall, the player's light sensors detect relatively little light when the laser beam is located over a pit.

A CD or DVD player uses a laser diode to produce its light. The 780-nm standard for CD players was adopted in 1980, when 780-nm infrared laser diodes were reliable but still fairly expensive. Technology advanced by the mid-1990s, however, and the 635- to 650-nm standard for DVD players reflects the development of inexpensive red laser diodes. New standards follow technology, so with the development of reliable blue laser diodes, new optical recording systems appeared. Blu-ray players and discs, which first appeared in 2006, are based on a 405-nm laser. Because a Blu-ray player can focus its blue laser beam to a much smaller spot than either a CD or a DVD player, a Blu-ray disc holds far more information than either of the earlier formats.

Check Your Understanding #2: The Blue Light Special

Blu-ray disc players use blue lasers with a wavelength of 405 nm in air or vacuum. A CD player uses an infrared laser with a wavelength of 780 nm. How must the pit depths in the reflective layer of a Blu-ray disc compare to the pit depths in a CD?

Answer: The pits in a Blu-ray disc must be about half as deep as those in a CD.

Why: The pits in the reflective layer should be about a quarter of a wavelength deep so that light reflected from the bottom of a pit interferes destructively with light reflected from an adjacent flat region. Halving the wavelength of the laser light requires halving the depth of the pits to achieve destructive interference.

The Optical System of a CD or DVD Player

A CD or DVD player's optical system measures the lengths of the tiny pits as they move by on a spinning disc. That reading process requires incredible precision. Not only must the player focus its spot of laser light exactly on the reflective layer, but it must also follow the spiral track as it moves by. The disc itself is neither perfectly flat nor perfectly round, so the player must continuously adjust its reading unit during playback. The optical system must keep its laser beam focused on the reflective layer (autofocusing) and must follow the track as it passes (autotracking). These two automatic processes are beautiful examples of the use of feedback.

The basic structure of a typical CD or DVD player is shown in Fig. 15.2.3. Light from a laser diode passes through several optical elements on its way to the disc's reflective layer. It comes to a tight focus on that layer, where it illuminates only a single track. Some light reflects from the layer and returns through the optical elements. Finally, the reflected light turns 90° at a special mirror called a polarization beam splitter and focuses on an array of light detectors. The player measures the electric currents flowing through the detectors and uses those measurements both to obtain data from the disc and to control the focusing and tracking systems.

Let's examine this optical system one element at a time. After leaving the laser diode, light passes through a *polarization beam splitter*. This device analyzes the light's polarization. As we saw in Section 14.1, different polarizations of light reflect differently when they strike a transparent surface at an angle. In this case, polarized light from the laser passes through the 45° surface, but light of the other polarization reflects. The beam splitter is specially coated to separate the two polarizations almost perfectly.

Light from the laser diode diverges rapidly as it passes through the beam splitter. It's not that the laser diode is broken or poorly designed; it's that a light wave emerging from a small opening naturally spreads outward, like ripples on a pond. This spreading is known as **diffraction** and occurs whenever a light wave is truncated by passage through an opening. The smaller the opening, the worse is the spreading. Because the emitting surface of the laser diode is essentially a very small opening, the laser beam spreads rapidly as it heads away from the diode. The player uses a converging lens located after the beam splitter to stop this spreading. At that point, the light beam is

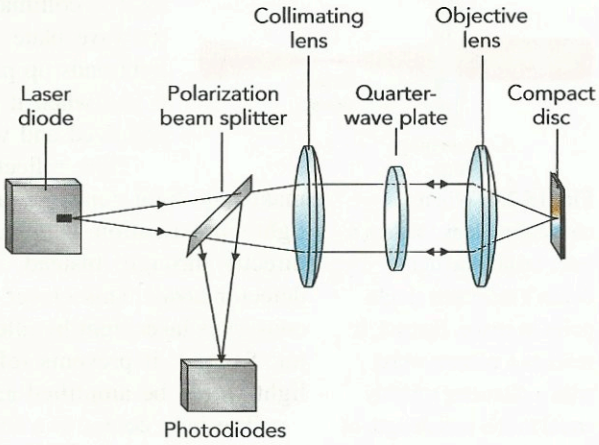


Fig. 15.2.3 In the optical system of a CD or DVD player, light from a laser diode passes through a polarization beam splitter, a collimating lens, a quarter-wave plate, and an objective lens before focusing on the reflective layer inside the disc. Reflected light turns 90° at the polarization beam splitter and focuses on an array of photodiodes.

already wide enough that diffraction causes little additional spreading. The beam leaves the lens *collimated*, meaning that it maintains a nearly constant diameter after passing through the lens.

The laser light then passes through a *quarter-wave plate*. This remarkable device performs half the task of converting horizontally polarized light into vertically polarized light or vice versa. Horizontally and vertically polarized lights are said to be **plane polarized** because their electric fields always oscillate back and forth in one plane as they move through space. The quarter-wave plate turns plane polarized light into circularly polarized light. We encountered circular polarization before in the radio transmissions from FM stations. In **circularly polarized** light, the electric field actually rotates about the direction in which the light is traveling.

Now the light passes through an objective lens that focuses it onto the reflective layer of the disc. On its way to the reflective layer, the light enters the plastic surface of the disc. At its entry point, the beam is still more than 0.5 mm in diameter, which explains why dust or fingerprints on the disc's surface don't cause much trouble. While contamination may block some of the laser light, most of it continues onward to the reflective layer.

The light comes to a tight focus just as it arrives at the reflective layer. Although it might seem that all of the light should converge together to a single point on that surface, it actually forms a spot roughly one wavelength in diameter. This spot size is limited by the wave nature of light. No matter how perfectly you try to focus light, you can't make a spot that's much smaller than the light's wavelength. Instead, the beam forms a narrow waist and then spreads apart (Fig. 15.2.4). This *beam waist* is about one wavelength of the light in diameter and a few wavelengths long, depending on the f-number of the converging lens. Since that waist is less than 2 microns long, the player's autofocusing system must keep the objective lens just the right distance from the reflective layer.

This fundamental limitation on how tightly a beam of light can be focused is another example of diffraction; the focusing lens truncates the light wave and inevitably introduces spreading. However, even reaching this ideal focusing limit requires careful design and fabrication of the optical elements. Although most other optical systems fall short of their ideal limits, a CD or DVD player's optical system does as well as can be done within the constraints of diffraction itself. Its optics are essentially perfect and are said to be *diffraction limited*.

The amount of light that reflects from the layer depends on whether or not the laser spot hits a pit. This reflected light follows the optical path in reverse. The light is collimated by the objective lens and then passes through the quarter-wave plate again. The plate now finishes the job it started earlier; the light ends up plane polarized, but with the opposite polarization from what it had when it left the laser. Horizontally polarized light is now vertically polarized and vice versa.

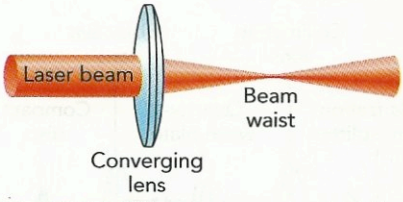


Fig. 15.2.4 When a converging lens focuses a laser beam, the light doesn't meet at a single point in space. Instead, it reaches a narrow waist with a diameter roughly equal to the wavelength of the light.

The reflected light then passes through the collimating lens, which makes the light converge, and then strikes the polarization beam splitter. Because the light's polarization has changed, the beam splitter no longer allows the beam to pass directly through. Instead, it turns this reflected beam 90° and directs it toward the detector array. This clever redirection scheme is important for two reasons. First, it conserves laser light by allowing most of it to travel from the laser diode to the detector. Second, it prevents reflected light from returning to the laser diode, where that light would be amplified and cause the laser diode to misbehave.

The light comes to a focus on an array of photodiodes. This array allows the player to detect pits via the reflected light intensity and also to determine whether the objective

lens is properly positioned relative to those pits. For generality, Fig. 15.2.3 omits optical elements involved in autofocusing and autotracking. However, because of those elements, the pattern of light hitting the detector array indicates which way the objective lens should move, if necessary. That lens is attached to coils of wire that are suspended near permanent magnets. By varying the currents flowing through those coils, the player uses Lorentz forces to move its objective lens about rapidly and keep it in the right place over the disc.

Check Your Understanding #3: That's Why It's Called a Laser Disc

Why must the CD or DVD player use a laser diode rather than a more conventional light source such as an incandescent bulb?

Answer: The light in a CD or DVD player must be coherent so that it can be focused to a single diffraction-limited spot on the reflective layer and experience destructive interference when it encounters a pit.

Why: You can't focus light from an incandescent bulb to a diffraction-limited spot. Each photon leaving the bulb is independent and will focus at a somewhat different point in space. The bulb's incoherent light also doesn't experience the strong interference effects of laser light.

Optical Fibers

Optical playback of prerecorded discs is fine for music and movies, but it isn't of much use when you want up-to-the-minute information. The Internet and World Wide Web require communication links that operate at lightning speed. Yet even here, optics and light have an important role to play. The fastest way to send enormous amounts of information is to use optical fibers.

An optical fiber is a glass conduit that guides light from one place to another. Nearly every photon that enters the fiber at one end emerges from the other end moments later. In its simplest form, the fiber is made from two different glasses: a solid core of one glass surrounded by a cladding of the other glass. Both glasses are so incredibly transparent that light can travel through them for kilometers with little loss. For comparison, look through the edge of an ordinary piece of window glass and you'll see how dark the glass looks. It absorbs far too much light to be suitable for optical fibers. They're made of the purest glasses known.

If both glasses are almost perfectly transparent, what keeps the light from leaking out of the sides of the fiber? The answer is a phenomenon known as total internal reflection. As light tries to move from the inner glass core to the outer glass cladding, it's reflected perfectly and thus can't escape.

Total internal reflection is an extreme case of refraction. When light encounters the boundary between two materials with different indices of refraction, refraction causes that light to bend (Fig. 15.2.5). If the material it enters has a smaller index of refraction than the one it leaves, the light bends away from a line perpendicular to the boundary. The amount of this bend depends on the two indices of refraction and on the angle at which the light approaches the boundary. As long as the approach angle is steep enough, light will succeed in entering the second material. However, if the approach angle is too shallow, the light won't enter the second material at all. Instead, it will reflect perfectly from the

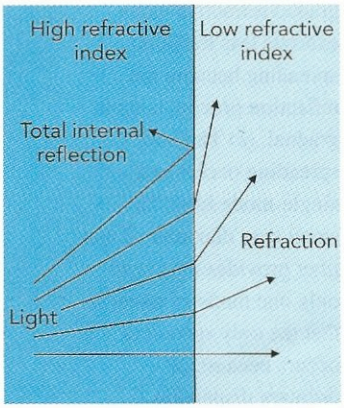


Fig. 15.2.5 When light traveling through one material enters a second material with a lower refractive index, it bends toward the boundary between those materials. If its approach angle is too shallow, the light will bend so much that it will simply reflect from the boundary. This effect is called total internal reflection.

boundary. In fact, total internal reflection is far more efficient at reflecting light than a conventional metal mirror.

To keep the light inside the fiber's core, the core glass must have a higher index of refraction than the cladding glass. As light in the high-index core encounters the boundary with the low-index cladding, it experiences total internal reflection and bounces back into the core (Fig. 15.2.6*a*). As long as the fiber doesn't bend too sharply, the light bounces back and forth inside the core and can't escape. As a result, light entering the fiber core through one of its cut ends follows the fiber all the way to its other cut end.

A large-diameter fiber (typically 50 μm or more) has a problem. Light rays bouncing through it at slightly different angles travel different distances during their passage through the fiber. Light heading almost straight down the center of the fiber rarely bounces and takes less time to complete its trip than light that bounces many times. Because this wide fiber has many bouncing paths or "modes" in which light can travel through it, a short pulse of light going through the fiber gets stretched out in time (Fig. 15.2.6*a*). This pulse-broadening severely limits the rate at which information can be sent through a multimode fiber.

To reduce stretching problems, the core of a better performance optical fiber has a graded refractive index. The core glass is specially treated so that its index of refraction decreases smoothly away from its center toward the cladding. Instead of bouncing abruptly when it reaches the boundary between core and cladding, light in this graded index environment turns smoothly back toward the core (Fig. 15.2.6*b*). The path differences between the modes in a graded index multimode fiber aren't so different, and a short pulse of light isn't stretched very much in a fiber of moderate length.

In very long fibers, however, even small path differences add up and short pulses become blurred in multimode fibers. Therefore, the highest performance optical conduits are single-mode fibers. These fibers have very narrow graded index cores that permit light to travel only in one mode—effectively right down the center of the fiber (Fig. 15.2.6*c*). The core is typically only 9 μm in diameter. A pulse of light entering this narrow core broadens very little in time during its passage.

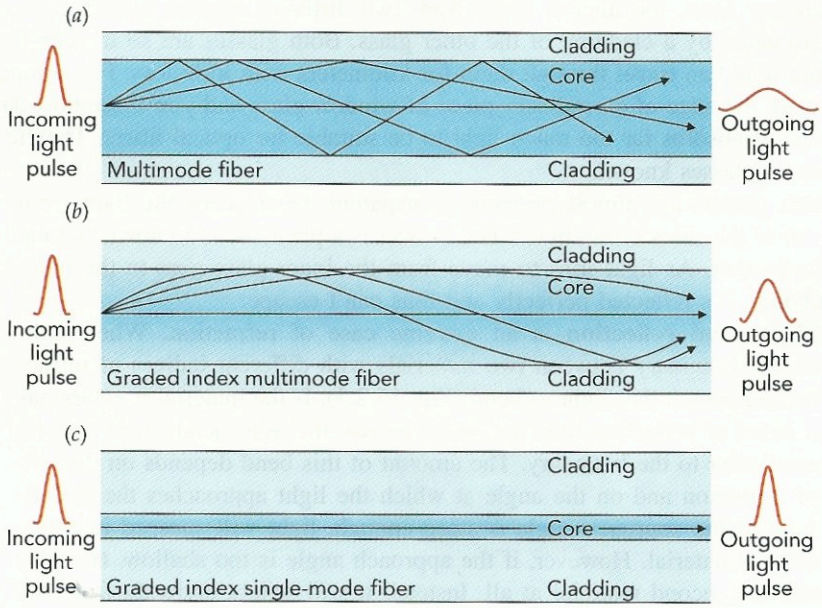


Fig. 15.2.6 Light trying to leave the high-index core of an optical fiber at a shallow angle undergoes total internal reflection at the boundary with the low-index cladding. (*a*) In an ordinary multimode fiber, a pulse of light can follow many paths through the core and becomes spread out in time. (*b*) A core with a graded refractive index exhibits less temporal spreading because the reflection process is more gradual. (*c*) The least spreading occurs in a single-mode fiber. The small core diameter of this fiber provides light with only one mode of travel so that the only spreading occurs because of ordinary dispersion.

What little broadening occurs in a single-mode fiber isn't caused by the light taking different paths; it's caused by ordinary dispersion in the glass. To carry information, the light wave must change with time and thus must have a range of frequencies and wavelengths. As usual, the shorter wavelengths travel slower than the longer wavelengths and the pulses get stretched out in time. To minimize these dispersion effects, the highest speed optical fibers operate at wavelengths that minimize dispersion. They also operate at wavelengths that minimize loss of light through absorption in the glass. These two wavelengths coincide at 1550 nm in so-called dispersion-shifted fibers, so this infrared wavelength is commonly used in long-haul optical communication.

Check Your Understanding #4: If It Looks Like a Mirror . . .

When you look into an aquarium from the front, the sides of the aquarium often look like mirrors. Those sides are actually clear glass, so why do they reflect light so well?

Answer: The light you see is experiencing total internal reflection as it tries to leave the glass at a shallow angle. You see perfect reflections of the fish inside the aquarium.

Why: Light has trouble passing from water or glass into the air at a shallow angle. When it tries, it experiences total internal reflection and bounces off the surface without losing any intensity at all.

Optical Communication

A typical optical communication transmitter uses a 1550-nm laser diode to generate short pulses of light. These pulses carry information from the transmitter to a receiver somewhere far away. The transmitter produces its pulses by varying the current passing through the laser diode. Light emerging from the laser diode is focused into the exposed core of a single-mode optical fiber, and it follows the core all the way to the other end of the fiber. When the light emerges, it's gathered by a lens and focused onto the receiver's photodiode. Each pulse of light causes a pulse of current to flow through the photodiode, allowing the receiver to begin processing the information.

A laser diode and a single-mode optical fiber can send billions of bits of data per second for 50 km or 100 km without significant errors. At longer distances, the gradual absorption of light in the glass makes it difficult to receive the information reliably. The easiest solution to this problem is to receive the data before the light becomes too weak and then to retransmit it with another laser diode.

Instead of interrupting the optical transmission with a receiver and retransmitter, some long-haul communication systems employ erbium-doped fiber amplifiers (EDFAs). An EDFA is a piece of optical fiber that has about 0.01% erbium ions in its glass core. When the EDFA is exposed to 980-nm or 1480-nm light, it becomes a laser amplifier for 1550-nm light. As the weakened pulses of light from a long fiber pass through the fiber amplifier, the amplifier duplicates photons and brightens the pulses. These amplified pulses then continue through ordinary fiber before being amplified again. Undersea optical cables often splice fiber amplifiers into the fibers every 50 km or so. These amplifiers allow light to travel thousands of kilometers through a continuous path, from one side of an ocean to the other.

To get the most out of a single optical fiber, many communication systems use several laser diodes operating at somewhat different wavelength ranges around 1550 nm. Light from these diodes is merged together and focused into the fiber. When the light

emerges at the far end of the fiber, its different wavelength ranges are split apart and directed onto individual receivers. The different wavelength ranges are like different channels, so that this wavelength-division multiplexing allows one fiber to carry far more information than it could with light from a single laser. Remarkably enough, an EDFA can amplify all of these different channels at once because erbium ions can copy a wide range of wavelengths.

Check Your Understanding #5: **Making Something Out of Nothing**

If light weakens gradually as it passes through a long optical fiber, why can't you simply wait until the very end of the fiber to amplify what little light remains and then send the amplified light into a receiver?

Answer: As the light is absorbed, the number of photons in a pulse gradually diminishes. When that number gets to zero, there's nothing left to amplify.

Why: Each pulse of light in the fiber contains a limited number of photons. The glass absorbs many of these photons during their long passage through a fiber, so they must be amplified before their numbers become so small that there's a chance that none of them makes it at all.

Epilogue for Chapter 15

In this chapter we looked at several common objects and studied the ways in which they use optics. In *cameras*, we saw how a converging lens can form a real image of an object and how that real image can be used to record a scene on a piece of film or an image sensor chip. We learned about the roles of focal length and f-number in determining the size and brightness of the real image and explored some of the complications that must be considered when designing lenses.

In *optical recording and communication*, we looked at how laser light is affected by various optical devices and looked at what happens to it when it's focused to a small spot. We learned about total internal reflection and how this effect makes it possible to send light hundreds or thousands of kilometers through a fiber of ultraclear glass.

Explanation: Focusing Sunlight

The magnifying glass forms a real image of the sun on the sheet of paper. Because the sun is so far away, the image distance between the lens and the paper is equal to the focal length of the lens. The real image is relatively small, yet it contains all of the sunlight that strikes the entire surface of the lens. With so much light focused onto a small region of the paper, the radiative heat transfer from the sun to the paper becomes quite large and the paper's temperature rises until it begins to smoke or burn. The lens's image also contains light from other parts of the sky, and this light can be seen surrounding the sun's disk. Because of the way light is bent during the formation of the real image, the clouds in the sky appear upside down and backward on the sheet of paper.

Chapter Summary

How Cameras Work: A camera lens projects a real image of the scene in front of the camera onto the image sensor inside the camera. This real image is formed when the lens bends all of the light reaching it from one part of the scene onto one part of the sensor. For this imaging process to work well, the distance between the lens and the image sensor must be adjusted so that the light converges together (focuses) just as it reaches the sensor. If the sensor is too close to or too far from the lens, the image is blurry. The depth of focus depends on the effective diameter of the lens—its aperture. The smaller the lens's aperture, the less critical the focus but the less light the lens gathers. A long focal length lens brings the light to a focus far behind it, forming a relatively large but dim real image on the image sensor. To brighten this image, the long focal length lens must have a large aperture so that it gathers lots of light. The f-number, the ratio of a lens's focal length to its aperture, characterizes the brightness of the lens's image.

How Optical Recording and Communication Work: A CD or DVD player uses a beam of laser light to read the pits on a thin reflective layer inside the disc. As the disc rotates, the pits pass through the focused laser beam and the amount of reflected light fluctuates up and down. The player monitors the reflected light and uses it both to recreate the music and to keep its optical system properly aligned. This continual realignment allows the player to follow the spiral track of pits as the disc turns and to keep the laser beam tightly focused on the reflective layer. The optical system, which includes a laser diode, several photodiodes, and a variety of lenses and other optical elements, is so well designed and executed that the spot it creates on the reflective layer is limited in smallness only by diffraction effects due to the wave nature of light.

Laser light can also carry information long distances through an optical fiber. Made from a core of extremely transparent glass, clad in a second glass, this fiber confines light via total internal reflection. As light attempts to leave the core at a shallow angle, it is perfectly reflected from the boundary with the cladding and continues through the fiber for great distances.

Important Laws and Equations

1. The Lens Equation: One divided by the focal length of a lens is equal to the sum of one divided by the object distance and one divided by the image distance, or

$$\frac{1}{\text{focal length}} = \frac{1}{\text{object distance}} + \frac{1}{\text{image distance}}. \qquad (15.1.1)$$

Exercises

1. On a bright, sunny day you can use a magnifying glass to burn wood by focusing sunlight onto it. The focused sunlight forms a small circular spot of light that heats the wood until it burns. Why is the spot of light circular?

2. Light passing through a curved water glass forms an image of the candle flame on the wall beside the table. Why would moving the candle toward or away from the glass spoil this effect?

3. Simple reading glasses are converging lenses that come in a variety of strengths, ranging from about 0.25 diopter (almost flat glass) to 3.00 diopters (highly curved). Which lens has the shorter focal length: 1.0 diopter or 2.0 diopters?

4. In a movie, an actor's eyeglasses send a brief undistorted reflection of the sun at the camera. Why does that simple reflection tell you that the glasses are props and that the actor doesn't need eyeglasses?

5. One part of a fiber optic communication system uses a lens to focus light from a semiconductor laser onto the end of an optical fiber. The tiny light source and fiber are on opposite sides of the lens, and each is 1.0 cm away from the lens. Why must the lens have a focal length of 0.5 cm?

6. Light from a distant object approaches the objective lens of a telescope as a group of parallel light rays. Draw a picture of the light rays from three stars passing through a converging lens to show that they focus at three separate locations.

7. Sports photographers often use large aperture, long focal length lenses. What limitations do these lenses impose on the photographs?

8. If you're taking a photographic portrait of a friend and want objects in the foreground and background to appear blurry, how should you adjust the camera's aperture and shutter speed?

9. Your new 35-mm camera comes with two lenses, a 50-mm focal length "normal" lens and a 200-mm focal length "telephoto" lens. The minimum f-number for the 50-mm lens is 1.8. Although the 200-mm lens has much larger glass elements in it, its lowest f-number is 4. Why is the telephoto lens's f-number so much larger?

10. If you hold your camera up to a small hole in a fence, you will be able to take a picture of the scene on the other side. However, the exposure time will have to be quite long, and the depth of focus will be surprisingly large. Explain.

11. Why does squinting increase your depth of focus?

12. Why is it easiest for the lens of your eye to form sharp images on your retina when the scene in front of you is bright and the iris of your eye is very small?

13. People who need glasses find it hardest to see clearly without them in dimly lit situations when the irises of their eyes are wide open. Why?

14. Photographic telescopes are simply enormous cameras. With such small f-numbers, they have small depths of focus. Why isn't that a problem for astronomical work?

15. Two similar looking magnifying glasses have different magnifications. One is labeled 2× (two times) and the other 4× (four times). Which lens has the longer focal length?

16. Which magnifying glass from Exercise 15 must you hold closer to the object you're looking at in order to see a virtual image of that object far in the distance?

17. The objective lens in a DVD player must move quickly to keep the laser beam focused on the disc's reflective layer. Why must this lens have a very small mass?

18. Why don't portable CD or DVD players play properly if you shake them back and forth too quickly?

19. What happens to a ray of light entering plastic from the air at an angle to the interface?

20. Why is a laser beam's focus delayed by its entry into the plastic of a CD or DVD? (Draw a picture.)

21. Why does a laser beam spread out quickly after it passes through a tiny pinhole?

22. Scientists measure the distance to the moon by bouncing laser light from reflectors left on the moon by the Apollo astronauts. This light is sent backward through a telescope so that it begins its trip to the moon from an enormous opening. This procedure reduces the size of the laser beam when it reaches the moon. Explain.

23. As it passes through the lens that focuses it onto a CD's aluminum layer, the player's laser beam is more than 1 mm in diameter. Why does its large size as it leaves the lens allow the beam to focus to a smaller spot?

24. Why can light from a blue laser form a narrower beam waist than light from an infrared laser?

25. Sometimes the surfaces of a glass of water look mirrored when you observe them through the water. Explain.

26. When you look into the front of a square glass vase filled with water, its sides appear to be mirrored. Why do the sides appear so shiny?

27. Some of the laser light striking a DVD's reflective layer hits the flat region around a pit and reflects back toward the photodiode. How does this reflected wave actually reduce the amount of light detected by the photodiode?

28. Why does the surface of a DVD look so colorful in white light?