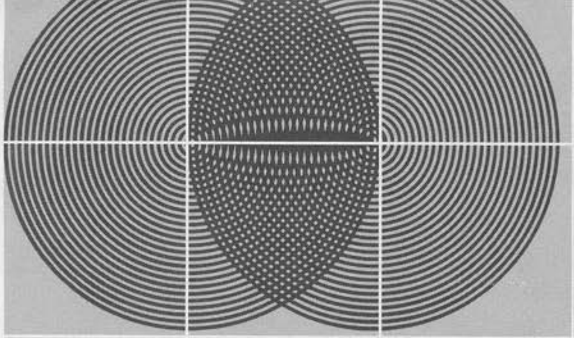

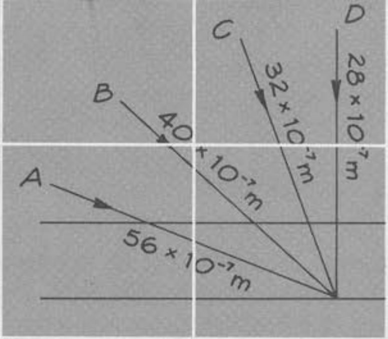

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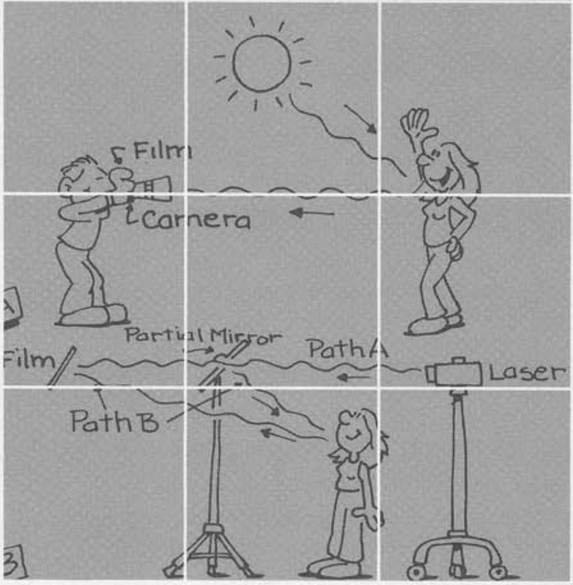
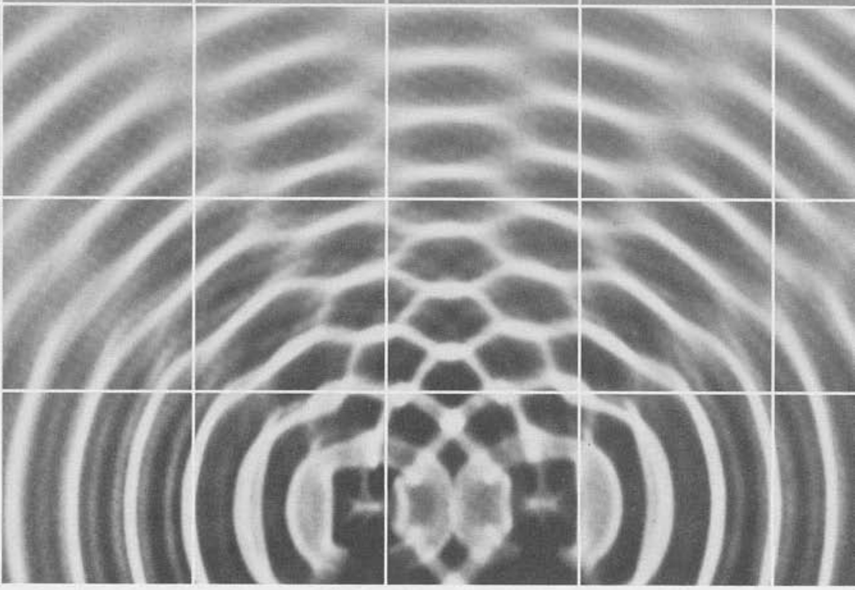




Interference and Diffraction

Despite its success in describing mirrors and mirages, the wave model of light met with formidable opposition during the seventeenth and eighteenth centuries. Although the wave model adequately explained the reflection, refraction, and absorption of light, a particle model of light offered what seemed to many physicists to be equally valid explanations of these phenomena. The ensuing wave-particle controversy over the nature of light offers a glimpse into how scientists deal with conflicting models.

Waves and particles offer two mechanisms for describing how energy gets from one place to another. Waves transfer energy but not matter. Particles transfer energy with matter. When phenomena are visible, distinguishing between the two models is relatively simple. Cars transfer energy like particles; springs transfer energy like waves. But when the phenomena are not visible, like sound, then distinguishing between the two models is more difficult. When we turn to light, we can see neither particles that carry the energy nor the medium responsible for transmitting the waves. The only way to distinguish between the two models is to find a behavior predicted by one model

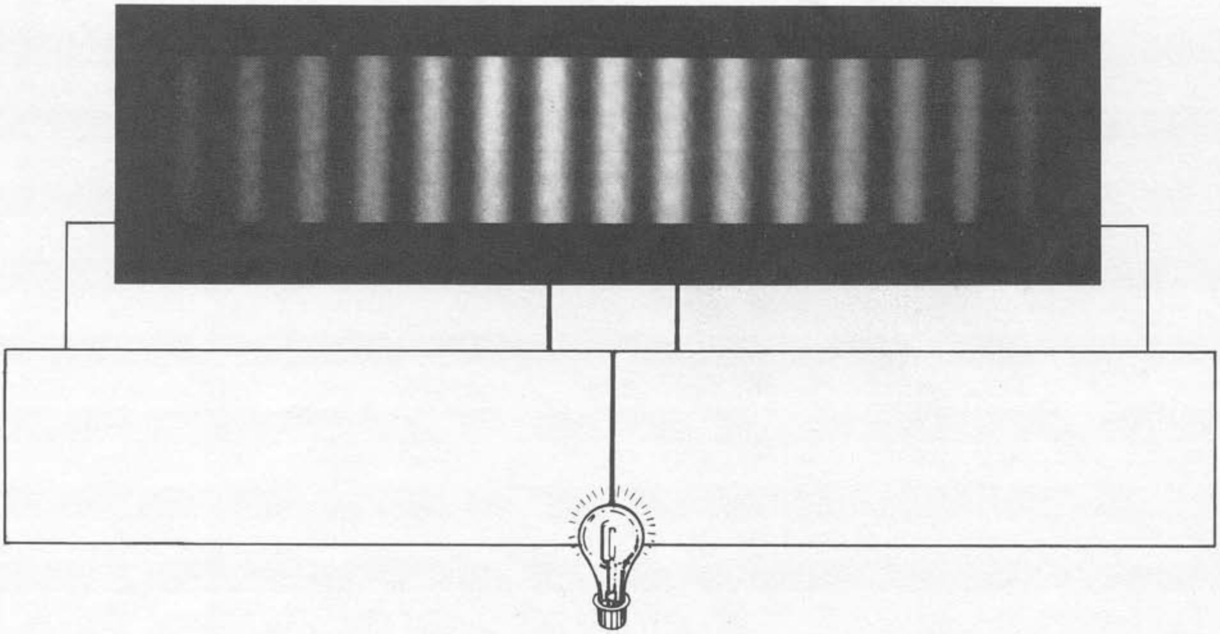


Figure 16-1

Young placed a barrier with a single slit and a second barrier with two slits between a light source and a screen. Instead of two bright slits, he saw a series of bright and dark bands spread across the screen.

but totally unexplained by the other. For the wave-particle controversy surrounding light, two phenomena—diffraction and interference—provided the critical test. At the turn of the nineteenth century these two phenomena could be explained only in terms of wave superposition.

In this chapter, we examine *interference* and *diffraction* of light in detail. Interference and diffraction effects were observed as early as the sixteenth century, but it was not until 1801 that Thomas Young explained light interference in terms of wave superposition. Later, diffraction was also explained in terms of the spreading and superposition of waves. You can see the effect of interference in the rainbow of colors reflected by oil patches and in the recently developed technology of *holography.* Diffraction of light plays an important role in photography and microscopy. Diffraction and interference were significant in temporarily resolving the wave-particle controversy, a controversy that would reappear as physicists began looking more closely at the structure of matter.

INTERFERENCE PATTERNS

In 1801 Thomas Young conducted what has become known as the Young double-slit experiment. As shown in Figure 16-1, Young placed two barriers between a light source and a screen. The first barrier had a single opening through which light could pass; the second had two such openings arranged side by side. The light transmitted by these two barriers produced a surprising pattern on the screen. Instead of two bright slits, Young saw a series of bright and dark slits spread across the screen. One way to understand these results is to look for similar patterns in other phenomena.

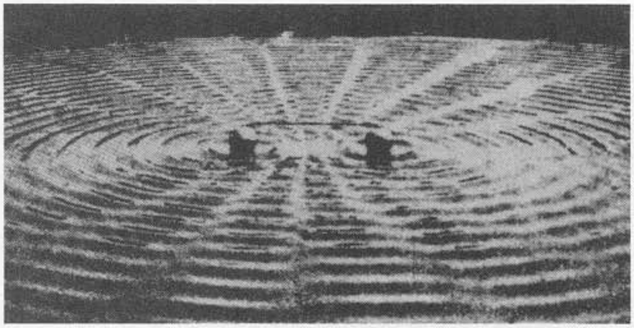


Figure 16-2

Circular waves produced by two sources spread out and combine to form a two-dimensional pattern. If we label the regions where nodes and antinodes occur along one dimension, we see Young's interference pattern.

Interference Patterns Occur with Waves

The pattern of bright and dark regions in Figure 16-1 is, in some ways, analogous to the antinodes and nodes formed by standing waves. The energy in standing waves is distributed unevenly. Nodes are areas in which no energy is found; antinodes are areas in which most of the energy is concentrated. If we think of these areas on the screen in terms of standing waves, the dark areas are nodes and the bright areas are antinodes. However, instead of being restricted to one dimension, like a standing wave on a rope, the bright and dark regions observed by Young are spread over two dimensions.

We can pursue this analogy further by looking for interference patterns in water waves. One way to create interference patterns in water is to attach identical beads to a piece of wood which can be vibrated at a constant rate. If this device is placed so that the two beads just touch the surface of the water with each vibration, each bead produces circular waves that spread continuously across the surface of the water. These waves overlap to produce a two-dimensional interference pattern (Figure 16-2). If we draw a line across the water's surface and label the regions where nodes and antinodes occur, we see the same pattern that Young observed with light. Nodes and antinodes alternate across the entire screen.

Use of Superposition of Waves to Explain These Patterns

Superposition of waves explains the patterns of nodes and antinodes shown in Figure 16-2. The two beads produce identical circular waves. As the two waves spread out and overlap with one another, constructive interference occurs wherever two crests or two troughs meet. Destructive interference occurs where a crest from one wave meets a trough from the other.

We can locate regions of constructive and destructive interference by comparing the distances the waves travel. Figure 16-3 gives an overhead view of the interference pattern. The most obvious region in which constructive interference occurs is the center line AB between the two wave sources S_1 and S_2. If we compare the distance traveled by one wave, S_1C, with the distance traveled by the second, S_2C, we find them to be equal. As the two waves arrive at C, a crest from one meets a crest from the other, and constructive interference occurs. The same result is true for any point along the

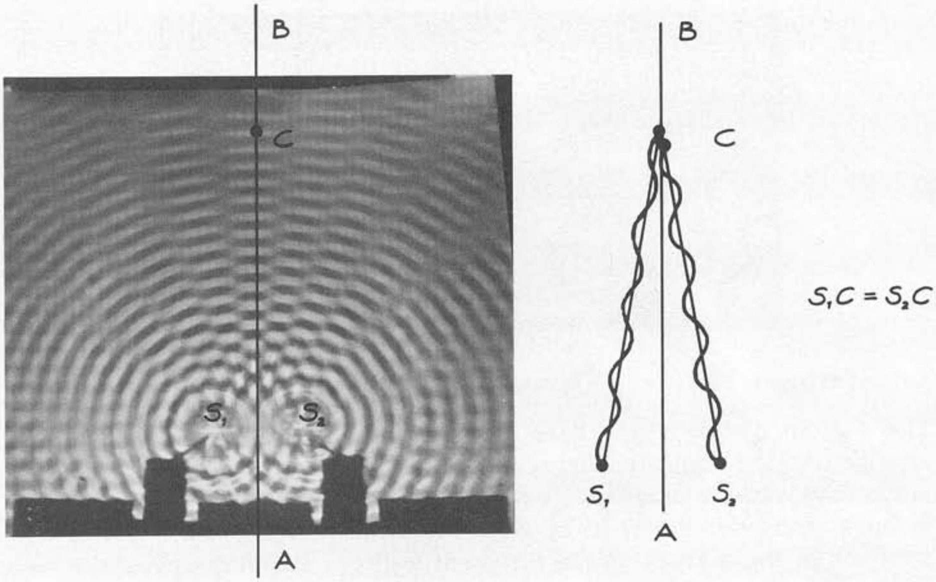


Figure 16-3

Since waves from each source travel the same distance, constructive interference occurs along the center line, *AB*.

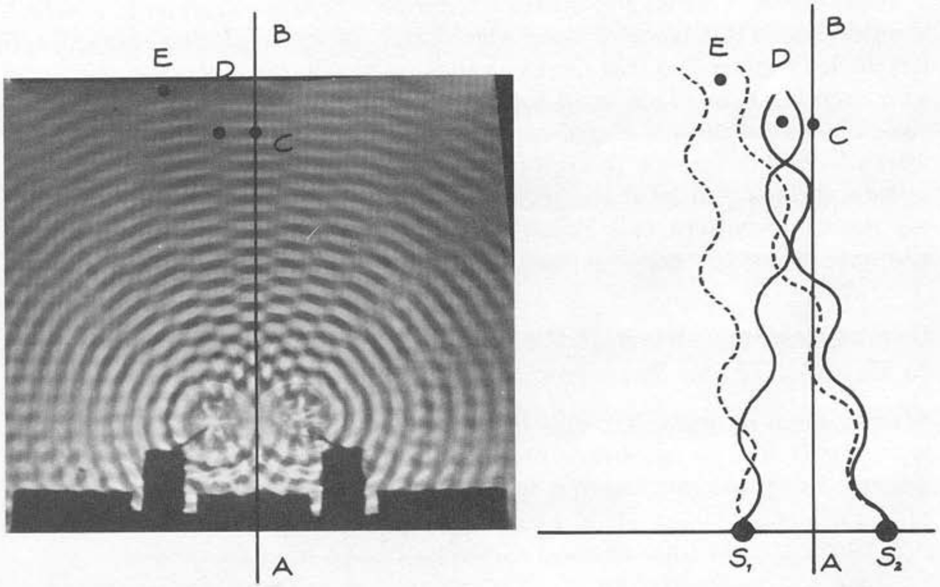


Figure 16-4

The type of interference, constructive or destructive, depends on the difference in the distances traveled by waves from S_1 and S_2. Destructive interference occurs at point *D*. Constructive interference occurs at point *E*.

center line, *AB*. The center line locates a series of double-amplitude crests and double-amplitude troughs.

To reach a point slightly to the left or right of the center line, one wave has to travel farther than the other. The magnitude of this extra distance determines whether the two waves interfere constructively or destructively. At point *D* in Figure 16-4, the wave emitted at S_2 has traveled a distance that is one-half a wavelength farther than the wave emitted at S_1. If the wave from

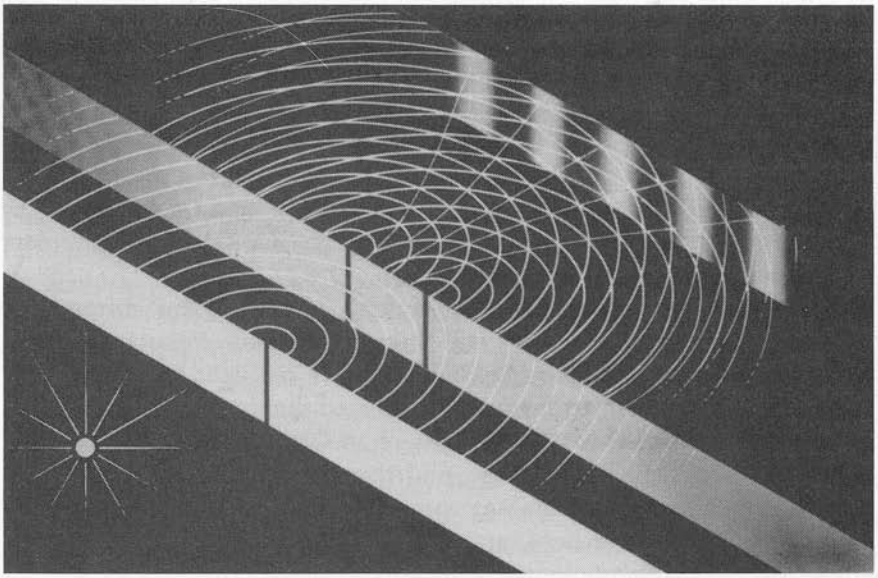


Figure 16-5

Water waves help us create a mental picture of how light waves spread out and overlap with one another to produce the pattern of bright and dark bands on the screen.

S_1 arrives as a crest, the wave from S_2 arrives as a trough, and destructive interference occurs. At E the wave emitted at S_2 has traveled a distance that is one complete wavelength farther than the wave emitted at S_1. If the wave from S_2 arrives as a crest, the wave from S_1 also arrives as a crest, and constructive interference occurs. We can continue to apply this analysis to each point along the surface of the water.

Because they arise from constructive and destructive interference of waves, patterns like the one in Figure 16-2 are called **interference patterns.** The regions of constructive and destructive interference are called **interference bands.** A band of constructive interference occurs where the distances traveled by the two waves are equal or where they differ by a whole number of wavelengths. Bands of destructive interference occur where the distances traveled by the two waves differ by an odd number of half-wavelengths. Thus

Constructive interference: $$\text{Extra distance} = n \text{ wavelengths} \qquad \text{where } n = 0, 1, 2, 3 \ldots$$

Destructive interference: $$\text{Extra distance} = \frac{n}{2} \text{ wavelengths} \qquad \text{where } n = 1, 3, 5, 7 \ldots$$

Applied to each point along the surface of the water, superposition of waves correctly predicts the observed interference patterns.

Photographs like Figure 16-2 give us a way of visualizing what happens in Young's experiment with light. Light waves transmitted through the two slits spread out like the circular waves produced by the two beads. The waves overlap, interfering constructively to produce bright bands and destructively to produce dark bands (Figure 16-5). Applied to each point along the screen, superposition of light waves correctly predicts the bright and dark bands Young observed.

SELF-CHECK 16A

Assume that water waves have a wavelength of 0.6 cm. The distance from S_1 to point I is 3.6 cm and from S_2 to I is 4.5 cm. Predict whether the waves interfere constructively or destructively at point *I*.

Seeing Interference of Light

When Young conducted his experiments, interference patterns like that in Figure 16-1 had never been observed. You have probably never seen one when you have looked through two narrow openings. Young saw them because he chose narrow slits that were very closely spaced.

The separation between interference bands depends on three variables: how far away from the wave sources we observe them, the separation between the two wave sources, and the wavelengths of the waves emitted by the two sources. Figure 16-6 shows the effect of the distance from the wave sources. The farther away from the wave sources you observe the pattern, the more the interference pattern spreads out. Figure 16-7(a) and (b) shows

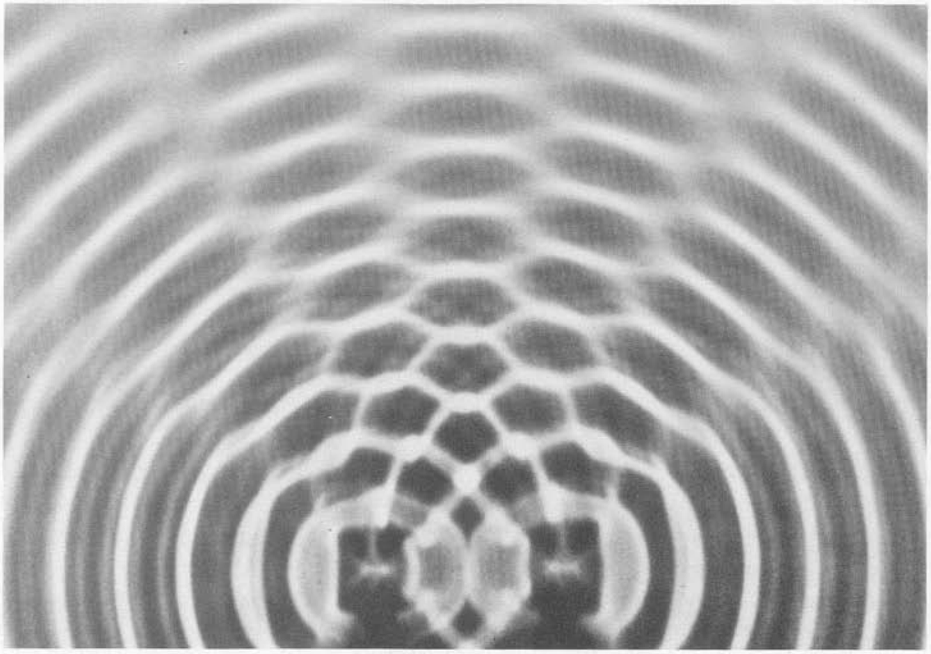


Figure 16-6
Interference bands spread out as we move away from the sources.

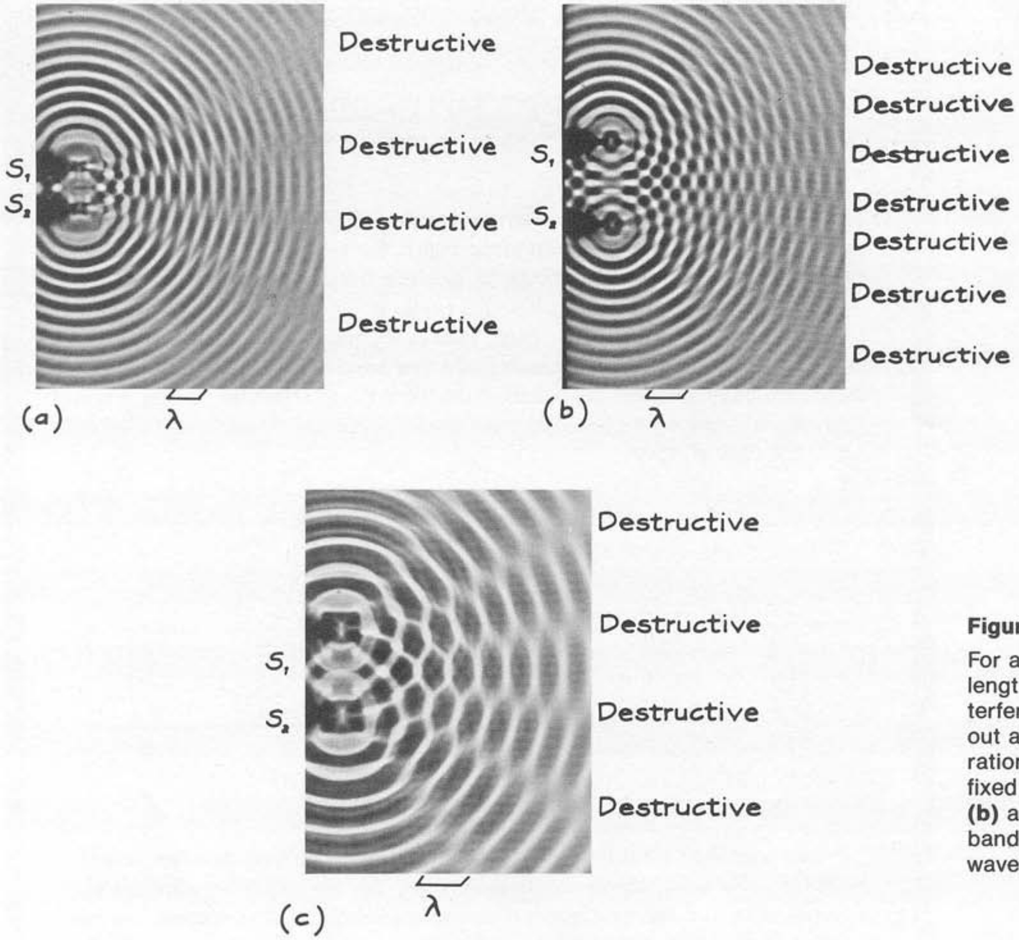


Figure 16-7

For a constant wavelength, **(a)** and **(b),** interference bands spread out as the source separation decreases. For a fixed source separation, **(b)** and **(c),** interference bands spread out as the wavelength increases.

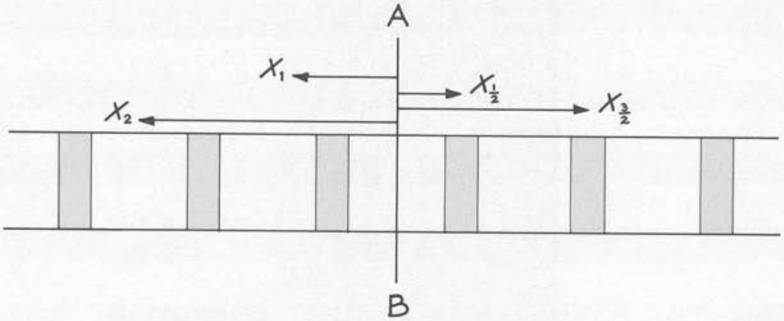
the effect of the separation between wave sources. The wavelength is the same, but the wave sources are more separated in (b) than in (a). As the separation between sources increases, the interference bands become more compressed, more closely spaced. Finally, Figure 16-7(b) and (c) shows the effect of wavelength. As the wavelength increases, the interference bands spread out.

As mentioned in Chapter 15, the wavelength of visible light is extremely small—about 5×10^{-7} meters (m) long. The interference bands produced by waves of such small wavelengths are so closely spaced that our eyes cannot resolve them. Slits spaced about a centimeter apart will produce interference bands that are separated by a distance less than the thickness of a strand of hair. The only way to spread the pattern out is to place the slits as close together as possible and observe the pattern as far from the slits as possible. Two slits less than a millimeter apart will produce interference bands separated by several millimeters on a screen 1 m from the slits. Our eyes are able to resolve these separations. Young succeeded where others had failed partly because he experimented with slits that were extremely closely spaced.

A STEP FURTHER—MATH

DESCRIBING INTERFERENCE PATTERNS QUANTITATIVELY

We can describe interference patterns quantitatively in terms of the location of each interference band. As shown in the figure, the location of each interference band can be described in terms of its distance from the center line, *AB*. X_1, X_2, X_3, . . . refer to the distances from the center of the pattern to the first band of constructive interference, second band, third band, and so on. $X_{1/2}$, $X_{3/2}$, $X_{5/2}$, . . . refer to the distances from the center to the first band of destructive interference, the second band, the third band, and so on. Since the interference pattern is symmetrical about the center line *AB*, these distances can be measured to either the left or the right of center.



As described in the text, these distances depend on three variables: how far away from the wave sources we measure them, the separation between the two wave sources, and the wavelength of the waves emitted by the sources. We can combine these relationships into a single expression for the distance from the center line to the center of each interference band:

Constructive interference:

$$X_n = \frac{(n)(\text{distance from source})(\text{wavelength})}{(\text{separation of sources})} \qquad n = 1, 2, 3, \ldots$$

Destructive interference:

$$X_{n-1/2} = \frac{(n - \frac{1}{2})(\text{distance from source})(\text{wavelength})}{(\text{separation of sources})} \qquad n = 1, 2, 3, \ldots$$

To see how these relationships can be applied to interference patterns, we examine the pattern produced by two slits 1 cm apart.

Let's calculate the distance from the center line to the middle of the *first* band of constructive interference. We need to know the distance from the source, the wavelength of light used to produce the interference bands, and the separation between the two slits. We assume that we are using red light with a wavelength of 6.5×10^{-7} m. The two slits are separated by 1 cm, a little less than half an inch. If we place a screen 1 m from the two slits, then the distance from the

$$\underbrace{X_n}_{\text{Constructive interference}} = \frac{n\,\overbrace{D}^{\text{Distance from sources}}\,\overbrace{\lambda}^{\text{Wavelength}}}{\underbrace{d}_{\text{Source separation}}}$$

$$\underbrace{X_{n-\frac{1}{2}}}_{\text{Destructive interference}} = \frac{(n-\frac{1}{2})\,\overbrace{D}^{\text{Distance from sources}}\,\overbrace{\lambda}^{\text{Wavelength}}}{\underbrace{d}_{\text{Source separation}}}$$

source is just 1 m. Substituting this information into our equation we have:

$$X_n = \frac{(n)(\text{distance from source})(\text{wavelength})}{(\text{separation of sources})} \qquad \text{for } n = 1$$

$$X_1 = \frac{(1)(1\text{ m})(6.5 \times 10^{-7}\text{ m})}{(1 \times 10^{-2}\text{ m})} = 6.5 \times 10^{-5}\text{ m}$$

6.5×10^{-5} m is equivalent to 0.065 mm. This distance is less than the width of a strand of hair! A separation of 1 mm produces a band of constructive interference 0.65 mm away from the center line. A separation of 0.1 mm produces a band 6.5 mm away—a distance easily noticed.

INTERFERENCE PHENOMENA

Young's double-slit experiment was important to nineteenth-century physics because it was the first phenomenon explained wholly in terms of light waves. Once understood in terms of wave superposition, Young's patterns provided the basis upon which a variety of everyday phenomena could be explained. More recently, they have provided the basis for a new technology—holography.

Interference Colors

The interference pattern in Figure 16-1 was created using a single color of light and captured on black-and-white film. Had we seen the actual pattern created by white light, we would have seen a central white region with bands of yellow, magenta, and blue-green to the right and left. You may have seen colors like these when looking at light through a lace curtain. Called **interference colors,** these bands arise from the different wavelengths of visible light that combine to form white light.

As shown in Figure 16-7(b) and (c), the spacing of interference bands depends on the wavelengths of the waves emitted by the two sources. As the wavelengths increase, the interference bands spread out. With its longer wavelength, red light (6.5×10^{-7} m) produces interference bands that are more spread out than those produced by blue-violet light (4.5×10^{-7} m). Although slight, this difference is enough to produce interference colors.

One way to explain interference colors is to look at the position on the screen where the various colors interfere destructively. Because of its longer wavelength, red light will interfere destructively farther from the center line than blue light. As shown in Figure 16-8, blue light interferes destructively at point *A*, green light at point *B*, and red light at point *C*. At point *A* we see white light minus blue light, which leaves yellow. At *B* we see white light minus green light, or magenta. Finally, at *C* we see white light minus red light, which leaves blue-green light. Bands of yellow, magenta, and blue-green are

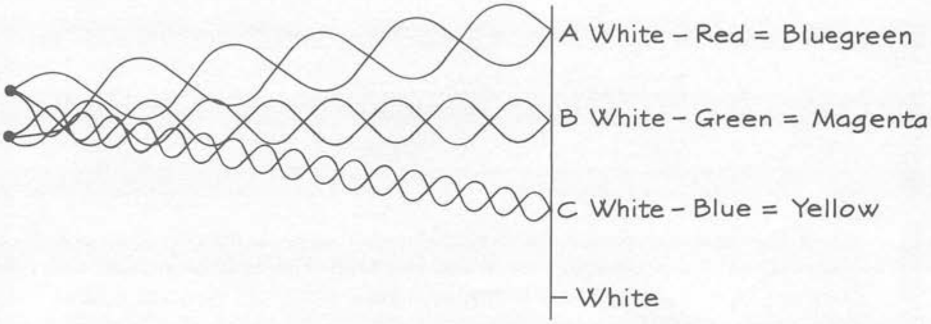


Figure 16-8

Each color interferes destructively at a different location. The color we see is white light minus the color that interferes destructively.

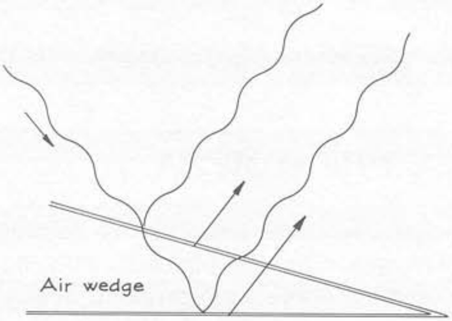


Figure 16-9

Light reflected by the bottom slide interferes with light reflected by the top slide.

formed on either side of a central white band, each the result of the absence of a particular wavelength due to destructive interference.

A lace curtain produces a similar effect because each opening in the lace acts as a slit. Rather than just two small openings, the curtain has many. The resulting pattern of colors is a little more complex. It is, however, produced by the same phenomenon—interference of white light as its waves pass through a series of narrow openings.

Interference Colors by Reflection

A puddle of water is covered by a thin layer of oil. As you walk by, you see a swirl of colors. Soap films left on dishes produce the same effect. You can see bands of color on soap bubbles as they float through the air. Water, soap films, and bubbles produce interference colors by reflecting light from two surfaces.

To understand how interference colors are produced by reflection, consider two pieces of glass arranged to form a V, as shown in Figure 16-9. Since glass both reflects and transmits light, the top and bottom piece will each reflect some light. However, light reflected by the bottom piece will have traveled farther than light reflected by the top piece. When this extra distance is an integer number of wavelengths (λ, 2λ, 3λ, . . .), light reflected by the top and bottom glass pieces interferes constructively. When it is an odd number of half-wavelengths ($\lambda/2$, $3\lambda/2$, $5\lambda/2$, . . .), it interferes destructively.

The pattern of colors we see depends on the wedge of air separating the two glass pieces. If the wedge of air is uniformly thick, we see a single color. If the air wedge varies in thickness, we see bands of different colors similar to the pattern in Young's double-slit experiment.

The bands of color that occur on soap bubbles and thin films of oil are produced by the same process. Light reflected from the top of the surface interferes with light reflected from the bottom surface. Since the thickness of the layers varies, swirls of color are produced.

SELF-CHECK 16B

Most camera lenses have a thin layer of material placed on their surfaces. When you look at these surfaces, they have a bluish appearance. What does this tell you about the thin layer of material? Does it vary in thickness?

Holography Records Images Using Interference Bands

One of the more exciting applications of interference by reflection is **holography**—a three-dimensional version of photography. In order to understand how this process produces a three-dimensional photograph, we need to contrast it with conventional two-dimensional photography. When you take a conventional photograph, you use sunlight or a flash attachment to provide a source of light. Light reflected by the object enters a camera lens (Figure 16-10(a)), which in turn directs it to the film. Photographic film responds to the amount of brightness of the light striking it. It simply adds together all the light that reaches it while the shutter is open, forming a two-dimensional image of the object.

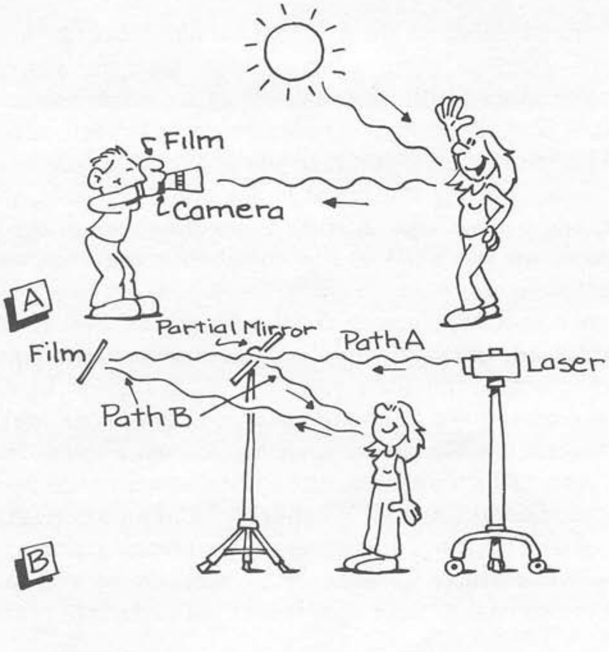
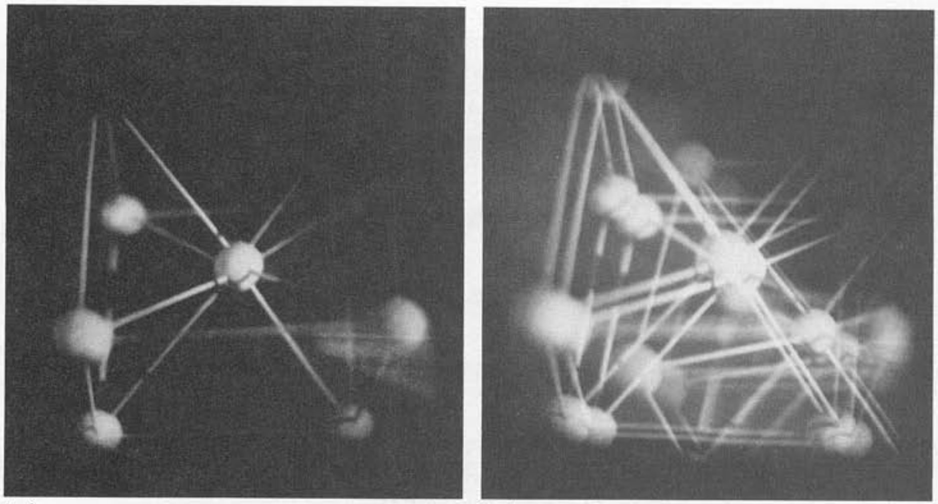


Figure 16-10

(a) Light reflected by the object is recorded on the photographic film in an ordinary camera. **(b)** Light from two paths interfere to record a hologram. Along path A, light travels directly from the laser to the photographic plate. Along path B, light travels from the laser to the object and then to the photographic plate.



(a) (b)

Figure 16-11

(a) A single three-dimensional image is produced with light of a single wavelength. **(b)** A mercury-arc lamp, which emits a mixture of five wavelengths, produces five three-dimensional images. Can you find them?

Holography differs from conventional photography in its ability to add information about the third dimension—the depth of the object. A hologram is produced by the interference between two laser light beams—one that is reflected from the object, as in conventional photography (path B in Figure 16-10(b)), and a second that travels directly from the laser to the photographic film (path A in Figure 16-10(b)). This second beam is often called the **reference beam.** When the reflected light interacts with the reference beam, they interfere. Since light reflected from a person's nose will have traveled a shorter distance than light reflected from his or her neck, the interference patterns for the two will be slightly different. Holography allows us to record information about the depth of an object because of the addition of a reference beam against which to measure the distance traveled by the reflected light.

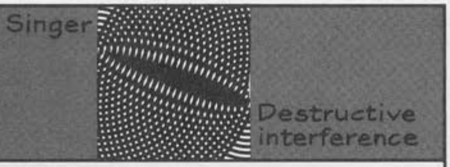
The pattern captured on the holographic film looks like a series of bright and dark bands—similar to but more complex than the simple interference patterns Young produced with his double-slit experiment. Stored in these interference bands is the information needed to reconstruct a three-dimensional image of the original object. If you hold the holographic film in front of a light source, light transmitted by the bright bands and blocked by the dark bands creates the image. The image is truly three-dimensional. As we move our viewing positions, we see parts of the object that were not visible from our earlier positions.

Interference patterns depend on wavelength as well as on the distance the light has traveled. Consequently, holograms are generally made with light of a single wavelength and then viewed with this same light. A hologram viewed with a mercury-arc lamp, for example, produces four separate images—one for each wavelength present in the light (Figure 16-11). You can imagine how confused a hologram would look when made by the complete spectrum of wavelengths found in white light. The information about the depth of the object becomes lost in the interference patterns produced by each separate wavelength. Lasers, which produce light of a single wavelength, offer the most convenient light source with which to record holograms.

Because the interference pattern recorded is specific to the wavelength of light with which it was made, we usually view the hologram with this same wavelength. If you hold a hologram in front of an ordinary light source, you will not see an image.

In conventional photography, a set of lenses is used to focus the light reflected from the object. As the reflected light spreads out from a point on the object, the lenses intercept a portion of the light and direct it to a point on the photographic film. Each point on the film corresponds to a point on the scene being photographed. In making a hologram, lenses are not needed.

Interference and Acoustics



All physicists seemed to agree that sound was a wave. Unlike light, observations of interference phenomena were not required to resolve any controversy. However, interference of sound waves has frequently been the critical point in a different kind of problem—the quality of sound in an auditorium.

A singer on stage emits sound waves that spread out and travel throughout the auditorium. When the sound strikes a hard surface, it is reflected. These reflections can travel back toward the stage and throughout the auditorium, interacting with the sounds later emitted by the singer. The law of superposition applies to these interactions. These results of these interactions affect what we hear. A particularly interesting effect occurs when the singer holds a note long enough that the frequencies of the reflected and emitted sounds are equal. Then, both constructive and destructive interference are possible. If the interference is constructive, the audience hears a note that is louder than the original. Destructive interference, however, means that they hear little or no sound—not very satisfying to the patron. One of many possible interactions is shown in the figure. The black semicircles locate the crests of each wave; the white semicircles identify the troughs. When the crest from the incident wave meets the crest from the reflected wave, constructive interference occurs. Destructive interference occurs at the solid dark areas, where a crest from one wave meets a trough from the other. As shown in the figure, reflections from the surface are capable of interacting destructively with incoming waves, leaving a wide swath of silence across the audience.

In an actual auditorium, the situation is much more complex. Sound reflects off all objects, resulting in many reflections that interfere constructively and destructively with each other, as well as with the original sound. These complications give rise to the difficulties architects face in designing concert halls. Even a good design can be less than ideal depending on the behavior of the audience. In one symphony hall, the designer assumed that the patrons would leave their coats at the checkroom. He included the possibility that sound would be reflected by the people in the audience and corrected for interference patterns accordingly. When the audience brought their coats into the hall, the reflections were slightly different and changed the interference patterns, albeit slightly.

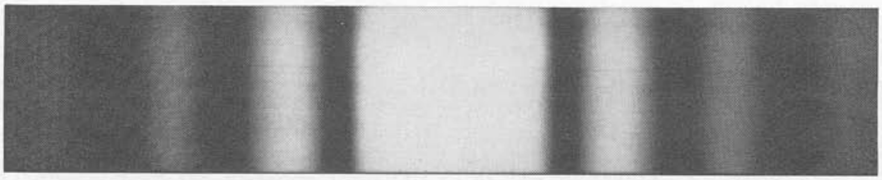


Figure 16-12
Light transmitted through a single slit produces a broad central band with bright and dark bands on either side.

Both the reflected and the nonreflected beams spread out across the photographic film. The pattern recorded on the film is made up of the interference of light reflected from every point on the object. If we cut the hologram into small segments, each segment contains a full interference pattern and, thus, the information necessary to reconstruct the entire image. Try that with a conventional photograph!

DIFFRACTION PATTERNS

In designing his double-slit experiment, Thomas Young was preoccupied with a search for evidence that light, like water and sound, experienced interference. The two slits in the second barrier acted as wave sources, providing waves that interfered with each other to produce the pattern shown in Figure 16-1. Had he removed the second barrier entirely, Young would have found additional evidence supporting the wave model of light. Instead of seeing a single band about the same width as the slit, he would have seen a much broader band with bright and dark bands on either side (Figure 16-12). Such a pattern is called a **diffraction pattern.** Light seems to spread out and interfere with itself as it passes through a single slit.

Waves Spread and Interfere

When straight water waves pass through an opening in a barrier, they spread out rather than producing a band of waves the same width as the opening (Figure 16-13(c)). At some distance from the barrier, the region across which energy has been transmitted can be considerably wider than the width of the opening through which the waves traveled. This spreading of waves after passing through a narrow opening is called **diffraction.**

The extent to which waves are diffracted depends on the width of the opening compared to the wavelength of the waves. The figure shows a series of experiments in which water waves of the same wavelength pass through openings of different widths. When the width of the opening is considerably larger than the wavelength (Figure 16-13(a)), very little diffraction occurs. As the opening narrows (Figure 16-13(b)), diffraction becomes more noticeable. When the opening becomes about the same size as the wavelength (Figure 16-13(c)), diffraction is substantial.

An additional characteristic of diffraction can be seen in Figure 16-13(b). If you look to either side of the broad central region in the diffraction pattern, you will notice that the wave crests seem to fade out, reappear, and then fade out again. A side view of the water's surface would show that the water re-

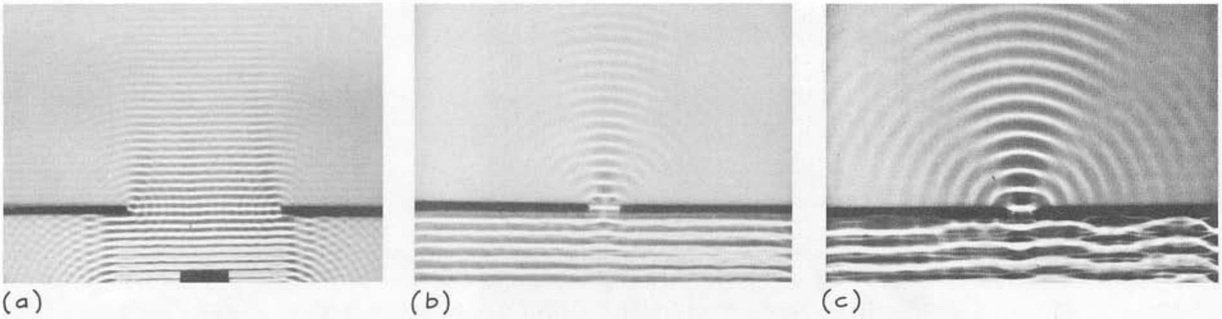


Figure 16-13
Diffraction becomes noticeable when the width of the opening and the wavelength of the water waves are about equal.

mains undisturbed in the regions where the pattern fades. As they are diffracted, water waves interfere to produce regions of constructive and destructive interference on each side of the central band.

SELF-CHECK 16C

Sound waves have wavelengths that range from a centimeter to several meters. Most voices produce sounds with wavelengths of about a meter. Light waves have wavelengths that are much smaller—averaging 5×10^{-7} m. Explain why sound is noticeably diffracted through doorways but light is not.

Superposition of Circular Waves Explains Diffraction

We can understand diffraction patterns if we imagine a straight-line wave as consisting of a series of individual circular waves. As each point in the water vibrates, it produces a circular wave that transmits energy in all directions. When several of these point sources vibrate together along a straight line, the individual circular waves combine to form the straight-line wave we actually see (Figure 16-14). We say that a straight-line wave is the sum of a series of waves from point sources, each producing circular waves that spread out and combine according to the principle of superposition.

This model for a straight-line wave explains why waves diffract as they pass through a narrow opening. Sources in the middle of the opening produce waves that combine to produce a straight-line wave. Sources near the edge of

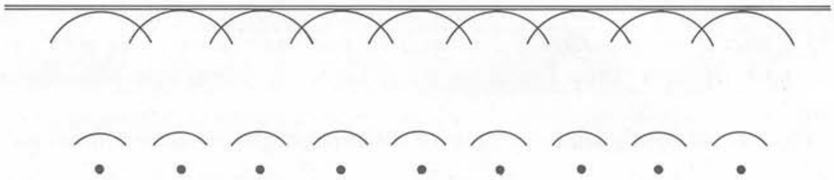


Figure 16-14
A straight-line wavefront can be constructed from a series of circular waves that have spread out from a line of point sources.

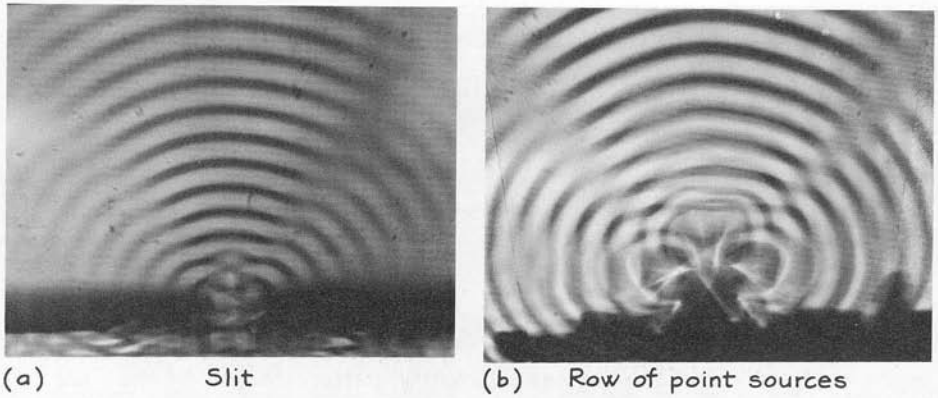


Figure 16-15

The interference pattern produced by a line of point sources in **(b)** looks almost identical to the diffraction pattern formed by a slit of equal width, shown in **(a)**.

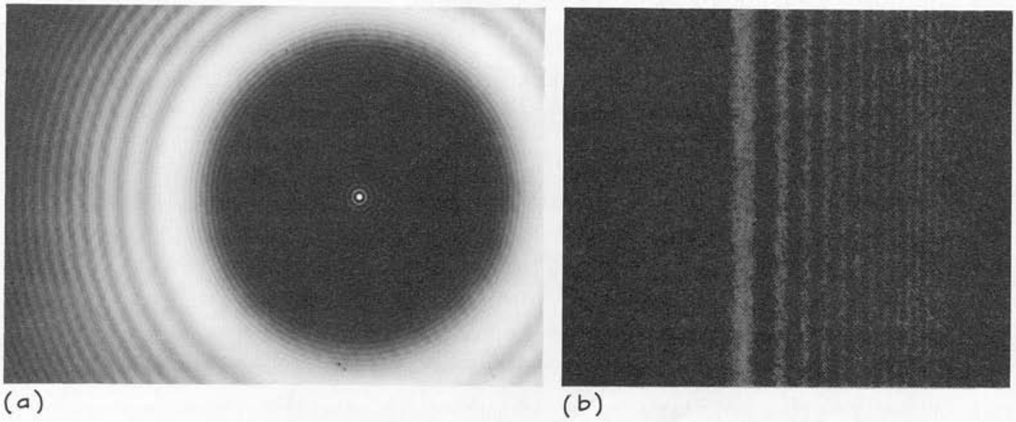


Figure 16-16

Diffraction patterns are formed as light passes through narrow openings or bends around small objects.
(a) Shadow of a penny.
(b) Shadow cast by a straight barrier.

the opening have nothing with which to combine, so their wavefronts remain circular. This bending at the edge of the pattern is what we call diffraction.

This model is equally effective in describing the bright and dark bands that accompany diffraction. Figure 16-15 shows a diffraction pattern formed by straight-line waves passing through a narrow opening (Figure 16-15(a)) and an interference pattern formed by a line of point sources (Figure 16-15(b)). The length of the row of point sources is the same as the width of the opening used to produce the diffraction pattern. Near the sources we see some differences in the two patterns. Far from the sources, however, the two patterns look identical. Circular waves passing through the slit combine to produce regions of constructive and destructive interference just like those due to waves from individual point sources.

Once again, the behavior of water waves helps explain the patterns produced by light passing through narrow slits. Before Thomas Young completed his work, physicists were not able to demonstrate diffraction consistently. Once they understood the need to provide openings as small as the wavelength of light, they found an abundance of diffraction phenomena to study.

Figure 16-16 shows a sample of diffraction patterns produced as light passes around obstacles or through openings of various shapes. Light is dif-

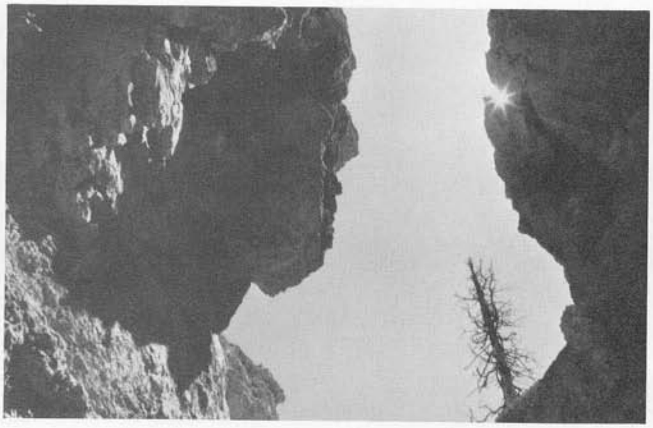


Figure 16-17

fracted, producing shadows larger than the obstacle or bright regions broader than the opening. Interference bands surround both the shadows and the central bright regions. One of the crowning achievements of the wave model of light was its success in predicting the small bright spot in the shadow formed by a penny (Figure 16-16(a)). Such a spot can arise only from the diffraction and interference of waves striking the edge of the coin.

SELF-CHECK 16D

For artistic purposes, photographers often like to capture the starlike effect shown in Figure 16-17. You can create similar patterns by squinting your eyes while looking at a light source. Use diffraction to explain how these patterns are produced.

DIFFRACTION AND RESOLUTION

The diffraction and interference of light waves produce striking and attractive patterns. The appeal of these phenomena diminishes, however, when we turn to the problems of designing optical instruments that produce faithful images. Instruments that use light to "see" must pass that light through some type of narrow opening. Because diffraction is created at each opening, cameras, microscopes, telescopes, and even the human eye face limitations due to diffraction.

Resolution of Closely Spaced Objects

Driving late at night, you see a distant car coming toward you. When it is very far away, its headlights all seem to blend together—you see only one light. As the car comes closer, you see headlights shining from both sides of the car.

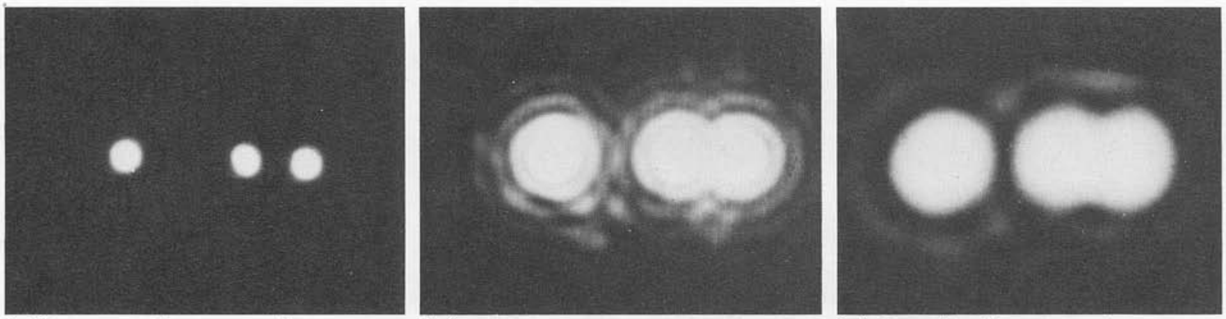

(a) Large-diameter lens (b) (c) Small-diameter lens

Figure 16-18

As the diameter of the lens decreases, we're less able to resolve the three point sources of light.

But, you still cannot tell whether each headlight is single or double. Finally, as the car comes still closer, you see the dual headlights on each side. Your difficulty in separating the four headlights is related to the resolving ability of the human eye.

The **resolution** of an optical instrument describes its ability to produce separated images of objects that are closely spaced. Two sources of light are resolved when we see separate images of them. Figure 16-18 shows a series of photographs of three closely spaced light sources. The pictures were taken through lenses identical to one another except in diameter. Each lens acts like a pinhole, providing a circular aperture through which light waves must travel. Because light is diffracted as it passes through small apertures, the images produced are slightly enlarged and fuzzy. When viewed through smaller and smaller apertures, they become so large and fuzzy that we are no longer able to resolve the three light sources.

Figure 16-18(a) was made with a relatively large-diameter lens, while Figure 16-18(c) was made with a small-diameter lens. As the diameter of the lens decreases, the diffraction of each image becomes more noticeable, just as the diffraction of the water waves increases as the passageway becomes narrower. We are able to distinguish three separate point sources for a large-diameter lens but are less able to do so as the diameter becomes progressively smaller. Because of diffraction, the image of each point source overlaps with the next. We say that the images cannot be resolved. The larger the lens, the better its resolution—that is, the more closely spaced the objects it can resolve.

One reason you are unable to resolve the distant set of headlights is related to the size of the pupil in your eye. Light must pass through this small opening in order to reach the retina. Diffraction occurs, causing the images produced to be fuzzy and slightly enlarged. When the images overlap, as they did photographically in Figure 16-18(c), you see two images instead of three.

Optical Instruments

Diffraction places some limitations on photographers. Cameras use adjustable apertures to control the amount of light that enters them. In a camera, the aperture is adjusted in a series of stages called *f*-stops—the larger the *f*-stop number, the smaller the aperture. Apertures usually range in diameter from a few millimeters to 20 or 30 millimeters. One of the most common problems with diffraction in a camera is that a small dot or point of light takes on fuzzy edges. While the pattern is not very noticeable on the film itself, it becomes obvious if the photograph is enlarged. Photographers who routinely take pictures intended for posters must be keenly aware of these effects.

Diffraction places a slightly different limitation on microscopes. Microscopes are designed to enlarge very small objects. The aperture size of the lens affects the resolving power of the instrument, just as it does for the camera and the eye. An additional problem is posed by the size of the objects the microscope is magnifying. Diffraction patterns become significant when the object being illuminated is the same size as the wavelength of light. Consequently, light transmitted or reflected by matter will not reveal the structure of objects smaller than 10^{-7} m. Microscopists have had to turn to electromagnetic waves of shorter wavelengths to investigate objects as small as those found within the cell.

SELF-CHECK 16E

The diameter of the pupil in the human eye averages 4 to 5 millimeters. The diameter of a large research telescope can be as much as 5 m. Use the problems posed by diffraction to explain why a large telescope should be able to resolve objects better than the naked eye.

WAVES VERSUS PARTICLES

The nature of light puzzled scientists for centuries. Most light phenomena—reflection, refraction, and absorption—could be explained as well by assuming light was a particle as by assuming it was a wave. For example, light is reflected so that the angle of reflection equals the angle of incidence. Balls are also reflected off walls so that the angle of reflection equals the angle of incidence. Light is refracted as it crosses a boundary between two media; balls, too, change speed and direction as they move into regions where different forces act. Light is absorbed by some forms of matter; objects stick together after certain kinds of collisions. True, physicists could not see the particles thought to carry light energy, but then, neither could they see a medium through which light waves could travel. One description seemed as reasonable as the other. However, when physicists observed interference and diffraction phenomena, the scales tipped in favor of the wave model of light. Diffraction and interference could not be explained by particle motion. They could only be explained in terms of wave superposition.

The wave-particle controversy surrounding the nature of light provides one of the most fascinating confrontations in science. Many people think that science concerns itself with facts—with measured observations about which there can be little disagreement. They are surprised to hear the word *controversy* used in this context. In reality, science deals with explanations and reasons for facts as much as with the facts themselves. Controversy about these explanations can and does arise quite often. Physicists agreed about the behavior of light as it was reflected, refracted, and absorbed by matter. The underlying reasons for these observations, described by some in terms of particles and by others in terms of waves, were what sparked the controversy. Only when they made additional observations were physicists able to resolve the controversy—temporarily.

The acceptance of the wave model of light provided two models for two types of phenomena. When energy is transmitted with an object, the particle model applies. When energy is transferred from a source to a receiver but matter is not, the wave model applies. At the beginning of this century, the dichotomy between the two models was well understood. Waves explained some phenomena; particles, other phenomena. This neat and clean separation between the two models was short-lived, however. Investigations into the structure of the atom blurred the distinctions and led to a renewal of the wave-particle controversy. The renewal of the wave-particle dilemma is the subject of the next chapter.

CHAPTER SUMMARY

Light from two slits or two point sources interacts to form a series of bright and dark bands on a distant screen. The resulting pattern, called an *interference pattern,* can be explained in terms of wave superposition. Constructive interference, producing the bright bands, occurs where the distances traveled by the two waves are equal or differ by a whole number of wavelengths. Destructive interference, producing the dark bands, occurs where these distances differ by an odd number of half-wavelengths. Interference bands are most noticeable when the separation between the light sources is about the same as the wavelength of light. We see interference patterns daily in the swirls of color reflected from oil and soap films. *Holography* uses interference bands to produce three-dimensional photographs.

Light from a single slit spreads out and interacts to form a broad band of light with light and dark bands on either side. The resulting pattern, called a *diffraction pattern,* can be explained in terms of circular wavelets. Each point in a wavefront acts as a point source for a circular wave. These individual wavelets combine to form the wavefronts we actually see. In a narrow opening, wavelets near each edge have nothing with which to combine, so they contribute to the spreading of the wavefront. This spreading is called *diffraction.* Within the opening, wavelets produce circular waves that can interfere constructively and destructively with one another. This interference produces the light and dark bands on either side of the central band. Diffraction patterns are most noticeable when the opening through which the waves travel is about the same size as the wavelength of light. Diffraction places limits on the ability of optical instruments to *resolve* images of separate objects that are closely spaced. Microscopes that use light to illuminate matter can only resolve structures larger than the wavelength of light.

ANSWERS TO SELF-CHECKS

16A. If we subtract the two distances, we find that waves from S_2 have traveled 0.9 cm farther than waves from S_1. This extra distance is $\frac{3}{2}$ times the wavelength of the water waves. The waves will interfere destructively at point *I*.

16B. Since we see just one color of light reflected from the lens, the thin layer must be uniformly thick. The thickness was chosen to allow blue wavelengths of light to interfere constructively while other colors interfere destructively. (This layer helps prevent unwanted reflection during photography.)

16C. Diffraction becomes most noticeable when the size of the opening is about the same size as the wavelength of the waves. A door is about 1 m wide. Sound has about the same wavelength, so sound waves are diffracted. Light has a much smaller wavelength, so we notice little diffraction.

16D. Diffraction of light as the sun is viewed through a narrow opening leads to the starlike effect. Light that passes near the edge of the opening spreads out, producing the streams that move outward from the source. When you squint your eyes, you create a narrow opening through which the light is diffracted.

16E. Light will be diffracted more by the pupil in the human eye than by the telescope lens because the lens is larger than the pupil. Since they diffract light less, telescopes should be able to resolve images better than the human eye.

PROBLEMS AND QUESTIONS

A. Review of Chapter Material

A1. Define each of the following terms:
Interference
Interference pattern
Interference colors
Holography
Diffraction
Diffraction pattern
Resolution

A2. In what ways are the bright and dark bands in Figure 16-1 analogous to nodes and antinodes in standing waves?

A3. Two identical waves travel from two different sources to a single point in the medium. What do you need to know in order to predict whether constructive or destructive interference occurs at that point?

A4. How does the interference pattern change if you change the distance from the source at which you observe it? If you change the wavelength of the waves? If you change the separation between sources?

A5. Why is white light separated into a series of interference colors after it passes through two closely spaced slits?

A6. How can interference patterns be produced by reflected light?

A7. How does the interference between the reference beam and the reflected beam contain information about the depth of an object?

A8. How does the diffraction pattern change when you change the width of the opening?

A9. How are individual point sources of circular waves used to explain the diffraction of a straight-line wave as it passes through a narrow opening?

A10. How are individual point sources of circular waves used to explain the interference bands in Figure 16-13(b)?

A11. How does diffraction affect the resolution of an optical instrument?

A12. Why were observations of interference and diffraction phenomena so crucial to the resolution of the wave-particle controversy in light?

B. Using the Chapter Material

B1. Two sources, S_1 and S_2, produce identical waves with wavelengths of 0.06 m. For each point described below, describe the type of interference that occurs—constructive, destructive, or in between.

Point Along Water's Surface	*Distance from* S_1	*Distance from* S_2
A	0.06 m	0.06 m
B	0.03 m	0.06 m
C	0.12 m	0.09 m
D	0.18 m	0.12 m
E	0.18 m	0.14 m

B2. Calculate the distance to the center of the first band of constructive interference for each situation described below. Use these distances to describe the way in which the interference pattern changes if we:

a. change the distance to the source

b. change the wavelength of the waves

c. change the separation between sources

Distance from Source	*Wavelength* (λ)	*Source Separation*
0.5 cm	6 cm	2 cm
1.0 cm	6 cm	2 cm
2.0 cm	6 cm	2 cm
1.0 cm	6 cm	30 cm
1.0 cm	6 cm	6 cm
1.0 cm	12 cm	2 cm
1.0 cm	2 cm	2 cm

B3. Red light with a wavelength of 7×10^{-7} m strikes a layer of gasoline that is 28×10^{-7} m thick. Will you see any red light reflected from the gasoline? Will you see any blue light with a wavelength of 4.3×10^{-7} m?

B4. Two slits are placed 1 mm (1×10^{-3} m) apart. A screen is placed 1 m from the two slits. Calculate the distance from the center line to the first band of destructive interference, $X_{1/2}$, for red light (6.5×10^{-7} m), green light (5.4×10^{-7} m) and violet light (4.0×10^{-7} m).

B5. Suppose you performed Young's double-slit experiment with red light, with green light, and with violet light. How would the interference patterns change as the color of light is changed?

B6. Seashells, butterfly wings, and bird wings often change color as you change the position from which you look at them. Use light interference to explain this phenomenon.

B7. When your car has a thin layer of oil on the windshield, you can see a rainbow of colors. Use light interference to explain why.

B8. Sound from two stereo speakers behaves like light traveling through two slits. If both speakers are emitting the same frequency of sound, would you expect to find regions where the sound is loud or soft? Why? Why do we not normally notice interference of sound with stereo speakers?

B9. Any point along a wave can itself be regarded as a point source of circular waves.

a. Draw 10 points, each separated from the next by 0.5 cm. Then draw circular arcs representing circular wave crests that have traveled 2.0 cm from their source. Show how these circular arcs combine to produce another straight-line wave.

b. Now imagine that these 10 point sources are equally spaced along a single slit. What happens to the circular wave produced by each point at the edge of the slit? Use this construction to explain diffraction of light by a single slit.

B10. Which would result in better resolution, a microscope that uses blue light or a microscope that uses red light? Why?

C. Extensions to New Situations

C1. Automobile headlights provide a common example of two sources of light. Yet we see no interference effects like those that occur in water. To understand why, let's begin with an analogy.

a. Suppose two friends are marching in step on the floor above you. Describe what you would hear.

b. Now suppose your two friends are just randomly walking about. What will you now hear? How is it different from what you described in (a)?

c. In both situations, (a) and (b), sound waves add according to the superposition principle. How does the pattern we hear depend upon whether the two people are marching in step or not?

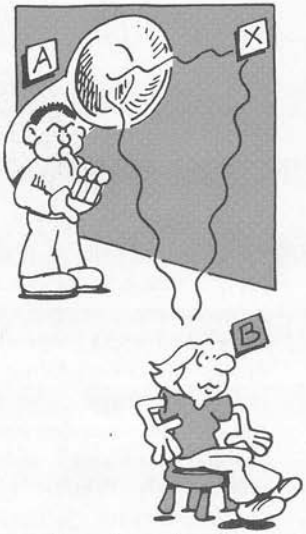
d. Most light sources, including automobile headlights, emit a steady stream of independent bursts of light that are generally out of step with those emitted by other sources. Use the analogy provided by (a)–(c) to explain why we do not see interference patterns like those in Figure 16-1.

C2. Ordinary light sources do produce interference patterns, but the bands constantly change because the light emitted by one source is out of step with the light emitted by a second source. Thomas Young and his contemporaries were familiar with the problem. Young's solution was to use a single slit in the first barrier that acts like a single point source of light. He then placed the second barrier such that the two slits, S_1 and S_2, were equidistant from the single slit.

a. How does this procedure ensure that the light rays passing through the two slits remain in step with one another?

b. Light passing through the single slit will be diffracted. In order to avoid problems posed by diffraction, should the second barrier be placed near or far from the first barrier? Explain your answer.

C3. Light from a single source can be reflected by two different surfaces, leading to an interference pattern. The same thing often occurs with sound waves. In this case, the sound wave emitted by a musical instrument often interferes with some of its reflection. As shown in the next column, the sound that traveled directly (along the path *AX*) interferes with the sound that was reflected from the floor (along the path *AB* + *BX*).



a. How would we decide whether point *X* was a region of constructive or destructive interference?

b. If the wavelength of sound is 1 m and the distances along *AX*, *AB*, and *BX* are 7 m, 6 m, and $5\frac{1}{2}$ m, respectively, will point *X* be a region of constructive or destructive interference?

c. What will a listener hear if he or she is located in a region of constructive interference? In a region of destructive interference?

d. This problem is a common one encountered by people who design concert halls. How might they solve this problem?

C4. As you walk by a puddle covered with gasoline, you see a changing rainbow of colors. This effect occurs because the difference in distance between the top and bottom layers depends on the actual path light has taken. The figure below shows four possible paths and the distances light travels to reach the bottom reflecting surface.

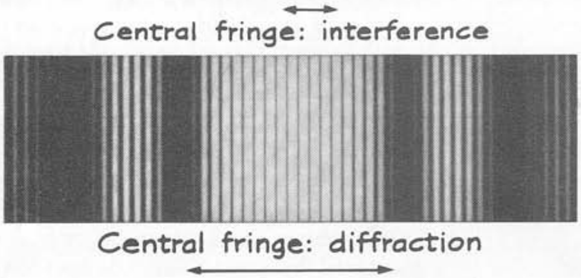
a. For each path, determine which wavelength interferes constructively and which interferes destructively.

b. Describe what you see as you walk from point *A* to point *B* to point *C* and finally to point *D*.

c. Does this explain the changing rainbow of colors you see?

C5. One way to take a photograph is with a pinhole camera. As its name implies, a pinhole camera is simply a box with a pinhole in one end and a piece of photographic film on the other end. When we open the pinhole, light travels into the box, exposing the film like a conventional camera. If the pinhole is too small, the image on the film will be fuzzy. Why?

C6. An interference pattern produced by two slits, the figure shows both the interference pattern and the diffraction pattern produced by the slits.



a. The narrow bands of bright and dark regions result from interference between light from the two slits. Measure the distances to the centers of the first two bright and dark bands.

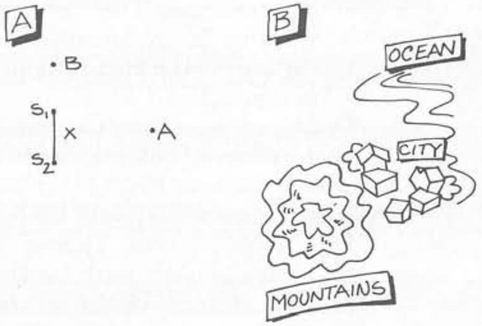
b. What happens to the bright and dark bands produced by interference as we move farther away from the center line?

c. The fading of interference bands arises from the diffraction pattern produced by each slit. How would the location of this fading change if the slits were made wider?

C7. You are casting a shadow on a wall. Near the wall, you see a shadow with sharp edges. As you move away from the wall, the edges become fuzzy. Why?

C8. Frequently scientists need to measure the wavelength of light emitted by a light source. We can use the spacing of interference bands produced by the double-slit experiment to provide such a measurement. Two slits are separated by 2×10^{-3} m. On a screen placed 1.5 m away, the distance from the center line to the first bright band was measured to be 4.4175×10^{-4} m. What was the wavelength of light emitted by the source?

C9. All electromagnetic waves are capable of producing interference patterns. Two radio towers broadcasting in all directions produce interference patterns that completely surround them. As shown in the figure below, two towers are separated by a distance *X*. Both towers emit identical waves of wavelength 500 m.



a. If the distance *X* is 500 m, predict what type of interference (constructive or destructive) will occur at points *A* and *B*.

b. If the two towers are placed closer together, $X = 250$ m, what type of interference occurs at *A* and *B*?

c. Use your answers to parts (a) and (b) to describe how the placement of radio broadcasting towers can be used to control the direction in which the signals travel.

d. How would you arrange two radio towers to broadcast 200 m waves to the city but not to the ocean or mountains (Figure 16-C9(b))?

D. Activities

D1. Look at lights through a very fine mesh such as fine lace curtains. Explain what you see in terms of interference.

D2. With a straight pin, make a number of different-sized holes in a piece of heavy paper. Look at light through each hole. Explain what you see.