31 DIFFRACTION AND INTERFERENCE

Objectives

- Describe what Huygens stated about light waves. (31.1)
- Describe what affects the extent of diffraction. (31.2)
- Explain how interference affects wave amplitudes. (31.3)
- Describe what Young's interference experiment demonstrated. (31.4)
- Explain how the colors seen in thin films are produced. (31.5)
- Describe how laser light is emitted. (31.6)
- Explain how a hologram is produced. (31.7)

discover!

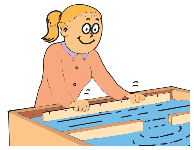
MATERIALS construction paper, container of water, clear nail polish

EXPECTED OUTCOME Students will see a pattern of iridescent colors on the nail polish film.

ANALYZE AND CONCLUDE

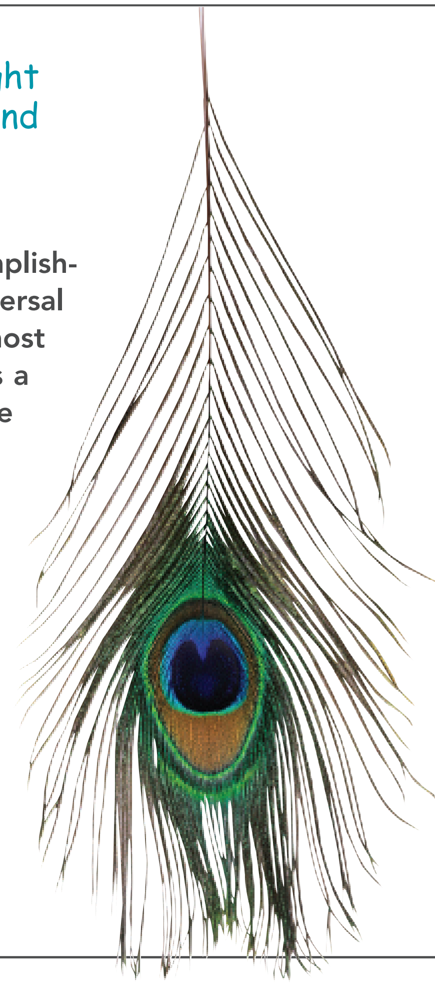
1. A pattern of iridescent colors
2. Different colors will be observed at different viewing angles.
3. Light incident on thin films is reflected from the top and bottom surfaces of the film. The interference of the reflected light as it exits the film gives rise to the iridescent colors.

31 DIFFRACTION AND INTERFERENCE



THE BIG IDEA The wave model of light explains diffraction and interference.

Today Isaac Newton is most famous for his accomplishments in mechanics—his laws of motion and universal gravitation. Early in his career, however, he was most famous for his work on light. Newton pictured light as a beam of ultra-tiny material particles. With this model he could explain reflection as a bouncing of the particles from a surface, and he could explain refraction as the result of deflecting forces from the surface acting on the light particles. In the eighteenth and nineteenth centuries, this particle model gave way to a wave model of light because waves could explain reflection, refraction, and everything else that was known about light at that time. In this chapter we will investigate the wave aspects of light to explain two important phenomena—diffraction and interference.



discover!

What Produces Iridescent Colors in Thin Films?

1. Submerge a piece of construction paper in a container of water.
2. Apply one drop of clear nail polish to the surface of the water and watch it spread out over the surface of the water.
3. After the nail polish has stopped spreading, slowly lift the construction paper out of the water. The nail polish should adhere to the surface of the paper.
4. Allow the paper to dry.

Analyze and Conclude

1. **Observing** What do you observe as you view the dried film on the surface of the paper?
2. **Predicting** What do you think you will see if you view the film from various angles?
3. **Making Generalizations** How would you explain the colors produced by thin films?

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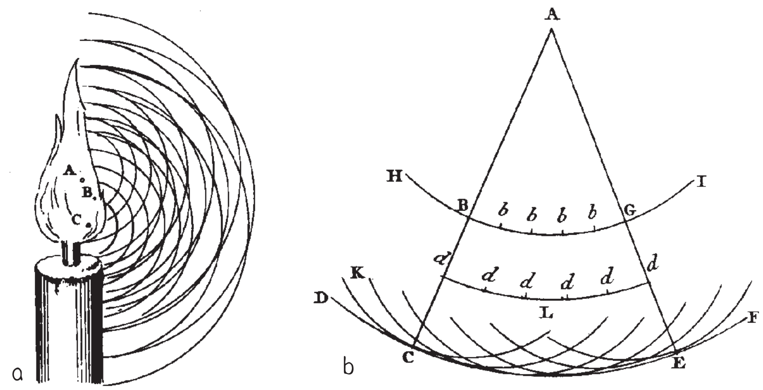


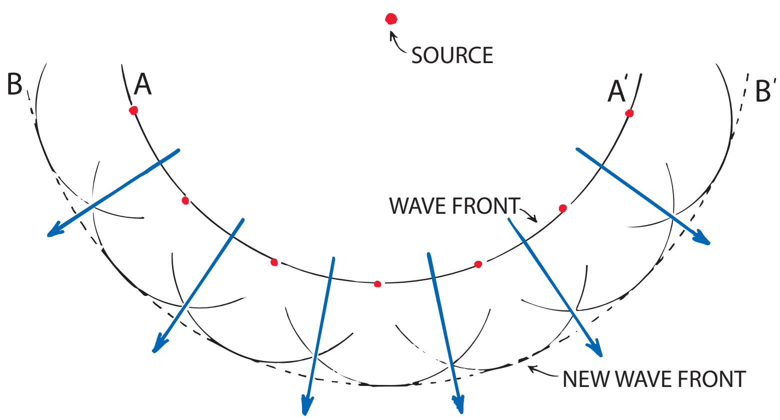
◀ **FIGURE 31.1**
These drawings are from Huygens' book *Treatise on Light.* **a.** Light from point *A* expands in wave fronts. **b.** Every point behaves as if it were a new source of waves.

31.1 Huygens' Principle

In the late 1600s a Dutch mathematician-scientist, Christian Huygens, proposed a very interesting idea about light. **Huygens stated that light waves spreading out from a point source may be regarded as the overlapping of tiny secondary wavelets, and that every point on any wave front may be regarded as a new point source of secondary waves.** We see this in Figure 31.1. The idea that wave fronts are made up of tinier wave fronts is called **Huygens' principle.**

Wave Fronts Look at the spherical wave front in Figure 31.2. Each point along the wave front *AA′* is the source of a new wavelet that spreads out in a sphere from that point. Only a few of the infinite number of wavelets are shown in the figure. The new wave front *BB′* can be regarded as a smooth surface enclosing the infinite number of overlapping wavelets that started from *AA′* a short time earlier.

As a wave front spreads, it appears less curved. Very far from the original source, the wave fronts seem to form a plane. A good example is the plane waves that arrive from the sun. A Huygens' wavelet construction for plane waves is shown in Figure 31.3. (In a two-dimensional drawing, the planes are shown as straight lines.)



◀ **FIGURE 31.2**
Every point along the spherical wave front *AA′* is the source of a new wavelet.

This chapter is best taught with a ripple tank of some sort—if not a commercial tank that shows detail on a screen, a large pan can serve your purposes. Put strips of screen mesh around the edges to reduce unwanted wave reflections. Use a large-diameter wooden dowel to generate waves. A gentle roll forward followed by a quick roll backward produces a nice single pulse. You control the frequency of additional pulses.

PAUL

31.1 Huygens' Principle

Key Term
Huygens' principle

▶ **Teaching Tip** Acknowledge Huygens' principle: Waves can combine to form bigger waves, and waves can also be considered as the superposition of still smaller waves.

Demonstration

Make plane waves in a ripple tank, aquarium, or large sink, using a ruler, as shown in Figure 31.5. A transparent container placed on an overhead projector works well. Use openings of various sizes to show how the amount of bending increases as the size of the opening decreases, as shown in Figure 31.6.

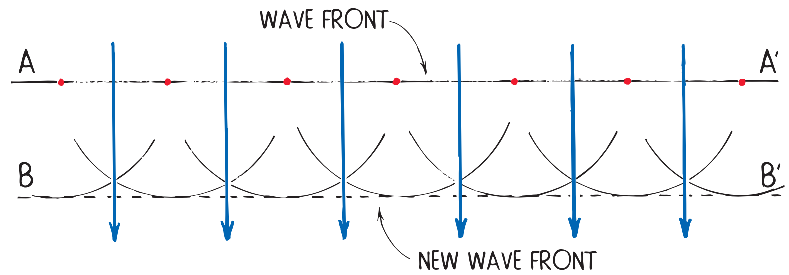


FIGURE 31.3 ▶
Far away from the source, the wave fronts appear to form a plane.

The laws of reflection and refraction are illustrated via Huygens' principle in Figure 31.4.

Huygens' Principle in Water Waves You can observe Huygens' principle in water waves that are made to pass through a narrow opening. A wave with straight wave fronts can be generated in water by repeatedly dipping a stick lengthwise into the water, as shown in Figure 31.5. When the straight wave fronts pass through the opening in a barrier, interesting wave patterns result.

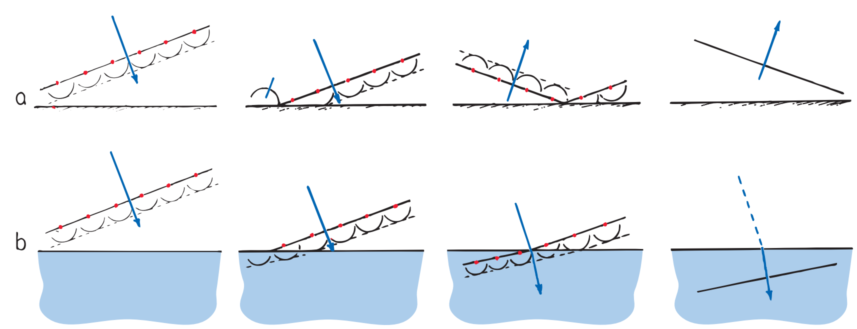


FIGURE 31.4 ▶
Each point along a wave front is the source of a new wave. **a.** The law of reflection can be proven using Huygens' principle. **b.** Huygens' principle can also illustrate refraction.

When the opening is wide, you'll see the straight wave fronts pass through without change—except at the corners, where the wave fronts are bent into the "shadow region" in accord with Huygens' principle. As you narrow the width of the opening, less of the wave gets through, and the spreading into the shadow region is more pronounced. When the opening is small compared with the wavelength of the waves, Huygens' idea that every part of a wave front can be regarded as a source of new wavelets becomes quite apparent. As the waves move into the narrow opening, the water sloshing up and down in the opening is easily seen to act as a point source of circular waves that fan out on the other side of the barrier. The photos in Figure 31.6 are top views of water waves generated by a vibrating stick. Note how the waves fan out more as the gap through which they pass becomes smaller.

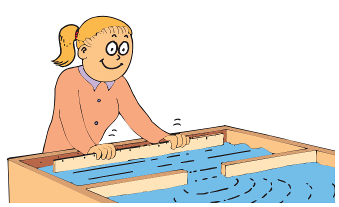


FIGURE 31.5 ▲
When plane waves are created in a tank of water, they produce a pattern as they pass through an opening in a barrier.

CONCEPT CHECK Huygens stated that light waves spreading out from a point source may be regarded as the overlapping of tiny secondary wavelets, and that every point on any wave front may be regarded as a new point source of secondary waves.

CONCEPT CHECK What did Huygens state about light waves?

Teaching Resources

- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

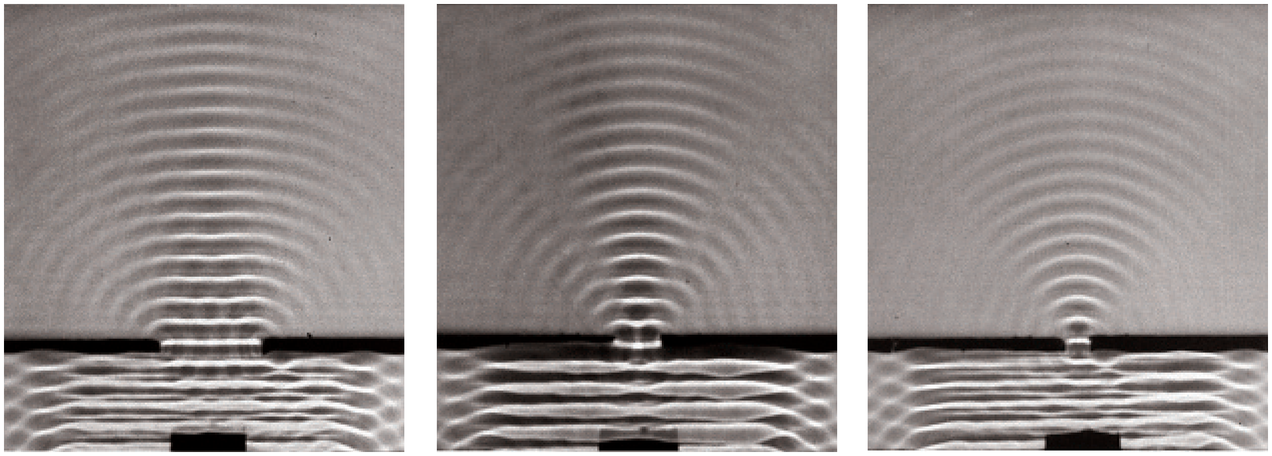


FIGURE 31.6 ▲
The extent to which the water waves bend depends on the size of the opening.

31.2 Diffraction

Any bending of a wave by means other than reflection or refraction is called **diffraction.** Figure 31.6 shows the diffraction of straight water waves through various openings. When the opening is wide compared with the wavelength, the spreading effect is small. As the opening becomes narrower, the diffraction becomes more pronounced. The same occurs for all kinds of waves, including light waves.

Diffraction of Visible Light When light passes through an opening that is large compared with the wavelength of light, as shown in Figure 31.7a, it casts a rather sharp shadow. When light passes through a small opening, such as a thin razor slit in a piece of opaque material, it casts a fuzzy shadow, for the light fans out like the water through the narrow opening, as shown in Figure 31.7b. The light is diffracted by the thin slit.

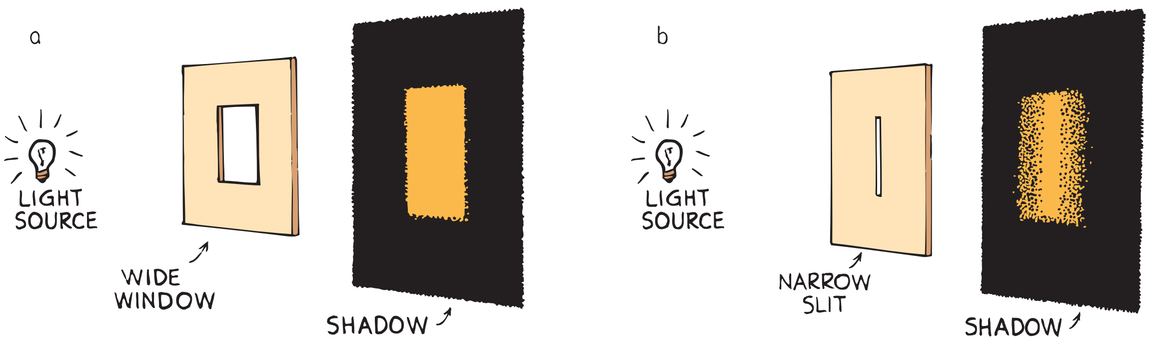


FIGURE 31.7 ▲
Diffraction occurs when light waves pass through an opening. **a.** Light casts a sharp shadow with some fuzziness at its edges when the opening is large compared with the wavelength of the light. **b.** Because of diffraction, it casts a fuzzier shadow when the opening is extremely narrow.

31.2 Diffraction

Key Term
diffraction

▶ **Teaching Tip** Introduce this topic by way of demonstrations. Point out that though you are using water to demonstrate the behavior of waves, these properties also apply to sound waves, light waves, and *all* other kinds of waves.

Demonstration

Show the diffraction of water waves in a ripple tank. Arrange objects in the tank to diffract waves through a variety of slit sizes.

Demonstration

Before class, paint a set of microscope slides black on one side. On each slide, scratch two closely spaced lines into the paint with a razor blade. Distribute the slides to your class. If they look carefully at a light source through the slits, they will observe an interference pattern. A monochromatic light source works best.

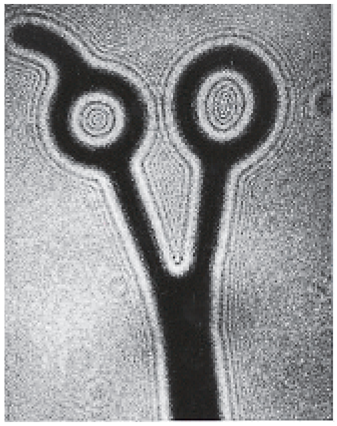


FIGURE 31.8 ▲
Diffraction fringes around the scissors are evident in the shadows of laser light, which is of a single frequency.

Diffraction is not confined to the spreading of light through narrow slits or other openings. Diffraction occurs to some degree for all shadows. Even the sharpest shadow is blurred at the edge. When light is of a single color, diffraction can produce sharp *diffraction fringes* at the edge of the shadow, as shown in Figure 31.8. In white light, the fringes merge together to create a fuzzy blur at the edge of a shadow.

Factors That Affect Diffraction ✓ **The extent of diffraction depends on the relative size of the wavelength compared with the size of the obstruction that casts the shadow.** This is illustrated in Figure 31.9. When the wavelength is long compared with the obstruction, the wave diffracts more. Long waves are better at filling in shadows. This is why foghorns emit low-frequency (long-wavelength) sound waves—to fill in "blind spots." Likewise for radio waves of the standard AM broadcast band. These are very long compared with the size of most objects in their path. Long waves don't "see" relatively small buildings in their path. They diffract, or bend, readily around buildings and reach more places than shorter wavelengths do.[31.2.1]

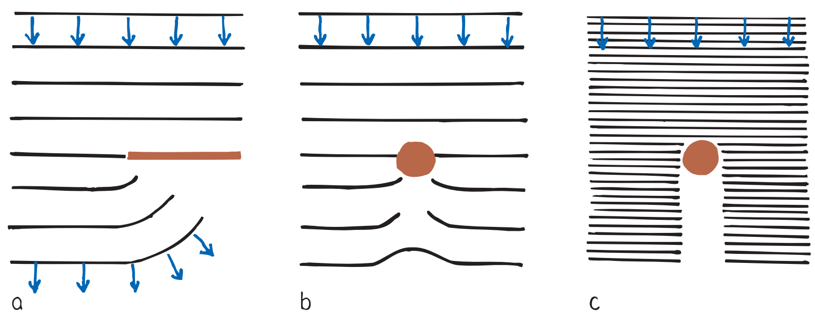
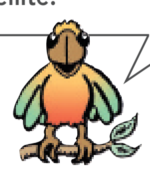


FIGURE 31.9 ▲
The amount of diffraction depends on the wavelength and the size of the obstruction. **a.** Waves tend to spread into the shadow region. **b.** When the wavelength is about the size of the object, the shadow is soon filled in. **c.** When the wavelength is short compared with the width of the object, a sharper shadow is cast.

Cable TV avoids "line-of-sight" transmission problems by sending the signal through a cable or optical fiber rather than "over the air." Satellite TV is line of sight, but normally without a mountain between you and the satellite!



Diffraction of Radio and TV Waves FM radio waves have shorter wavelengths than AM waves do, so they don't diffract as much around buildings, and aren't received as well as AM radio waves are in mountain canyons or city "canyons." This is why many localities have poor FM reception while AM stations come in loud and clear. TV waves, which are also electromagnetic waves, behave much like FM waves.[31.2.2] Both FM and TV transmission are "line of sight," meaning that obstacles between the transmission tower and antennas for receiving TV broadcasts can cause reception problems.

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Diffraction in Microscopy Diffraction is not so helpful when we wish to see very small objects with microscopes. If the size of the object is the same as the wavelength of light, the image of the object will be blurred by diffraction. If the object is smaller than the wavelength of light, no structure can be seen. This is why the bacteria you look at in a biology lab just appear as little dots or rods. The internal details are too small to be seen with visible light. No amount of magnification can defeat this fundamental diffraction limit.

To see smaller details, you have to use shorter wavelengths. A beam of electrons has a wavelength associated with it that can be a thousand times shorter than the wavelengths of visible light. Microscopes that use beams of electrons to illuminate tiny things are called *electron microscopes.* Because of the shorter wavelength used, the diffraction limit of an electron microscope is much less than that of an optical microscope.

think!

Why is blue light used to view tiny objects in an optical microscope?
Answer: 31.2

Diffraction and Dolphins Smaller details can be better seen with smaller wavelengths. This is cleverly employed by the dolphin in scanning its environment with high-frequency sound—ultrasound.[31.2.3] The echoes of long-wavelength sound give the dolphin, like the one pictured in Figure 31.10, an overall image of objects in its surroundings. To examine more detail, the dolphin emits sounds of shorter wavelengths. With these sound waves, skin, muscle, and fat are almost transparent to dolphins, but bones, teeth, and gas-filled cavities are clearly apparent. Physical evidence of cancers, tumors, heart attacks, and even emotional states can all be "seen" by the dolphins. The dolphin has always done naturally what humans in the medical field have only recently been able to do with ultrasound devices.

FIGURE 31.10 ▲
A dolphin emits ultrashort-wavelength sounds to locate and identify objects in its environment.

CONCEPT CHECK What affects the extent of diffraction?

discover!

Can You See Diffraction in the Sky?

1. Hold two fingers close together between your eye and an illuminated source such as the sky.
2. Look carefully at the narrow opening. Do you see diffraction fringes?
3. Vary the width of the opening, and the distance of your fingers from your eye.
4. Cut a thin slit in a piece of cardboard and repeat the experiment. (Vary the size of the slit by bending the cardboard slightly.)
5. **Think** How do the diffraction fringes change with the width of the slit?

▶ **Teaching Tip** After discussing diffraction, pass out to the class index cards with razor slits in them. Cover three segments of a fluorescent lamp with three sheets of colored plastic, red, clear, and blue. Have your students view the diffraction of these three segments through the slit or through a slit made with their own fingers. Students should note the different fringe spacings of different colors.

CONCEPT CHECK The extent of diffraction depends on the relative size of the wavelength compared with the size of the obstruction that casts the shadow.

Teaching Resources

- **Reading and Study Workbook**
- **Transparency** *74*
- **Presentation*EXPRESS***
- **Interactive Textbook**

discover!

MATERIALS piece of cardboard

EXPECTED OUTCOME Students will see diffraction fringes through the gap between their fingers and through the slit in the cardboard.

THINK As you vary the space between your fingers or the size of the slit in the cardboard, the interference pattern changes.

31.3 Interference

This topic was introduced in Chapter 25 and applied to sound in Chapter 26. If you did not show the *Light Waves* DVD back in Chapter 27, show it now.

PAUL

Demonstration

With the lights out, shine laser light through an irregular piece of glass (shower door glass, sugar bowl cover, crystal glassware, etc.) and display beautiful interference patterns on the wall.

The previous demonstration is a great one! It is especially effective if you make slight movements of the glass in rhythm with music. (I do it to Bach's Orchestral Suite No. 3.) Your students will not forget this demonstration!

PAUL

CONCEPT CHECK Within an interference pattern, wave amplitudes may be increased, decreased, or neutralized.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**
- **Next-Time Question** *31-1*

Go Online SCI LINKS NSTA

For: Links on interference
Visit: www.SciLinks.org
Web Code: csn – 3103

31.3 Interference

If you drop two stones into water at the same time, the two sets of waves that result cross each other and produce what is called an *interference pattern.* **Within an interference pattern, wave amplitudes may be increased, decreased, or neutralized.** When the crest of one wave overlaps the crest of another, their individual effects add together; this is *constructive interference.* When the crest of one wave overlaps the trough of another, their individual effects are reduced; this is *destructive interference.* Constructive and destructive interference of waves is illustrated in Figure 31.11.

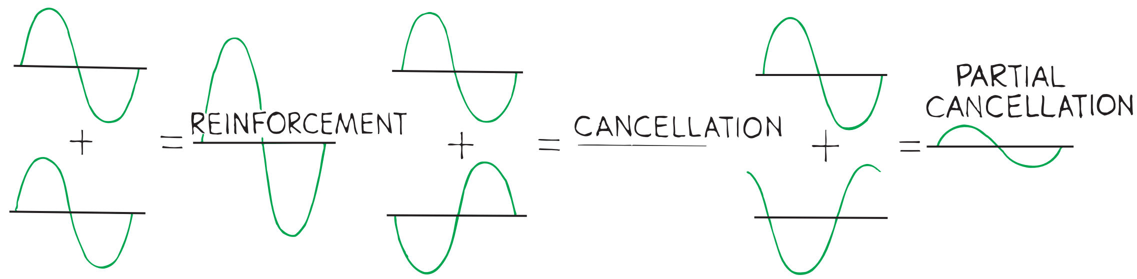
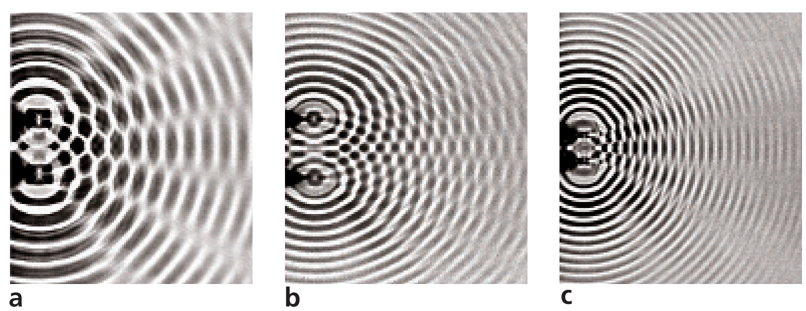


FIGURE 31.11 ▲
Waves can interfere with each other constructively or destructively.

Water waves can be produced in shallow tanks of water known as *ripple tanks* under more carefully controlled conditions. Interesting patterns are produced when two sources of waves are placed side by side. Small spheres are made to vibrate at a controlled frequency in the water while the wave patterns are photographed from above. The gray "spokes" are regions of destructive interference. The dark and light striped regions are regions of constructive interference. The greater the frequency of the vibrating spheres, the closer together the stripes (and the shorter the wavelength). Note in Figure 31.12 how the number of regions of destructive interference depends on the wavelength and on the distance between the wave sources.

CONCEPT CHECK How does interference affect wave amplitudes?

FIGURE 31.12 ▶
You can observe interference from overlapping water waves from two vibrating sources. **a–b.** The separation between the sources is the same but the wavelength in (b) is shorter than the wavelength in (a). **b–c.** The wavelengths are the same but the sources are closer together in (c) than in (b).



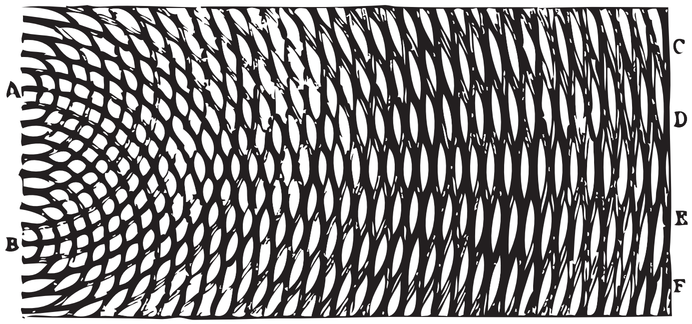


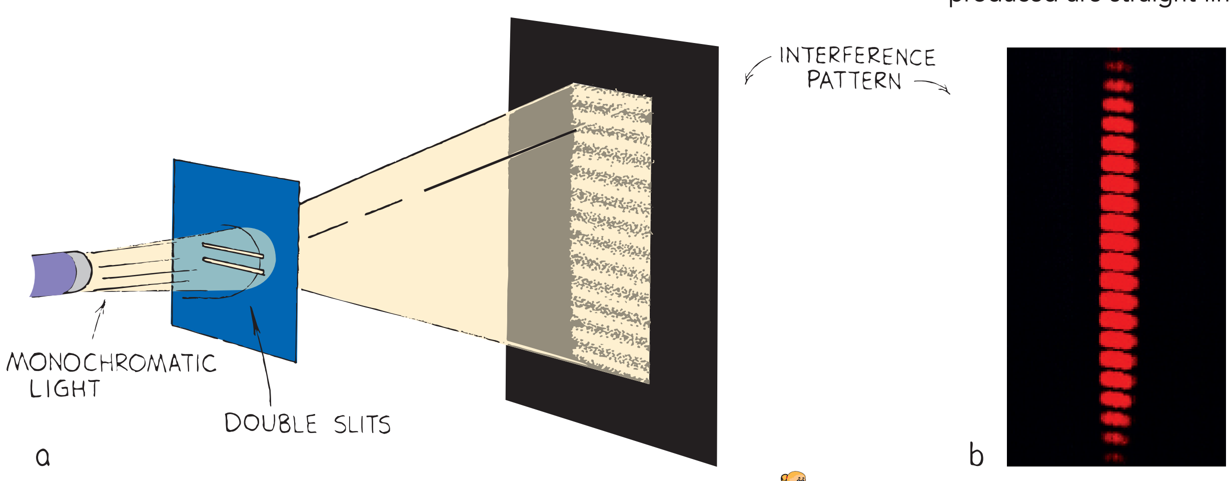
FIGURE 31.13
In Thomas Young's original drawing of a two-source interference pattern, the dark circles represent wave crests; the white spaces between the crests represent troughs. Letters *C*, *D*, *E*, and *F* mark regions of destructive interference.

31.4 Young's Interference Experiment

In 1801 the British physicist and physician Thomas Young performed an experiment that was to make him famous.[31.4] Young discovered that when **monochromatic** light—light of a single color—was directed through two closely spaced pinholes, fringes of brightness and darkness were produced on a screen behind. He realized that the bright fringes of light resulted from light waves from both holes arriving crest to crest (constructive interference—more light). Similarly, the dark areas resulted from light waves arriving trough to crest (destructive interference—no light). Figure 31.13 shows Young's original drawing of a two-source interference pattern. ✓ **Young's interference experiment convincingly demonstrated the wave nature of light originally proposed by Huygens.**

Double Slit Experiment Young's experiment is now done with two closely spaced slits instead of pinholes, so the fringes are straight lines. A sodium vapor lamp provides a good source of monochromatic light, and a laser is even better. The experimental arrangement is shown in Figure 31.14a. The pattern of fringes that results is shown in Figure 31.14b.

FIGURE 31.14
Young's interference experiment demonstrated the wave nature of light.
a. The arrangement for the experiment includes two closely spaced slits and a monochromatic light source.
b. The interference fringes produced are straight lines.



31.4 Young's Interference Experiment

Key Terms
monochromatic, diffraction grating

Common Misconception
Light cannot cancel light.

FACT Just like all waves, light can interfere constructively and destructively. Destructive interference of light causes cancellation.

▶ **Teaching Tip** Good plastic replicas of diffraction gratings are available through scientific supply companies and are quite inexpensive. Get a class set and distribute them. Have students describe their observations when looking at an incandescent light source. Set up neon, hydrogen, helium, or other gas spectrum tubes and have students observe the excited gas sources through the gratings.

▶ **Teaching Tip** Spend some time discussing Figure 31.15. It is important that students understand interference patterns before moving on.

CONCEPT CHECK Young's interference experiment convincingly demonstrated the wave nature of light originally proposed by Huygens.

Teaching Resources

- **Reading and Study Workbook**
- **Concept-Development Practice Book** *31-1*
- **Problem-Solving Exercises in Physics** *15-3*
- **Laboratory Manual** *87, 88*
- **Presentation*EXPRESS***
- **Interactive Textbook**

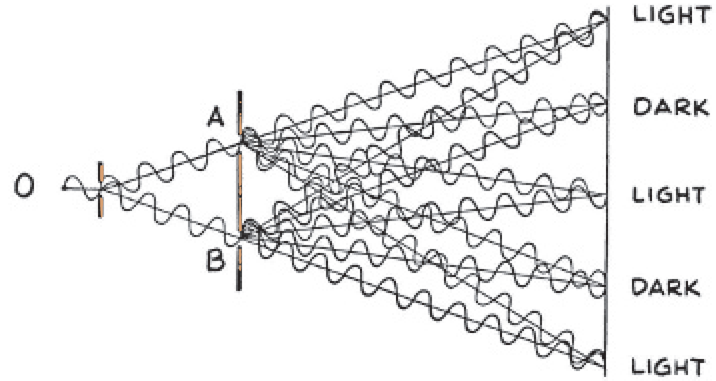


FIGURE 31.15 ▶
Light from *O* passes through slits *A* and *B* and produces an interference pattern on the screen at the right.

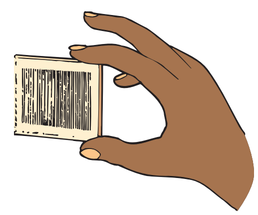
think!

Why is it important that monochromatic (single-frequency) light be used in Young's interference experiment?
Answer: 31.4

Figure 31.15 shows how the series of bright and dark lines results from the different path lengths from the slits to the screen. A bright fringe occurs when waves from both slits arrive in phase. Dark regions occur when waves arrive out of phase.

Diffraction Gratings Interference patterns are not limited to double-slit arrangements. A multitude of closely spaced parallel slits makes up what is called a **diffraction grating.** Many spectrometers use diffraction gratings rather than prisms to disperse light into colors. Whereas a prism separates the colors of light by refraction, a diffraction grating, such as the one shown in Figure 31.16, separates colors by interference.

FIGURE 31.16 ▶
A diffraction grating disperses light into colors by interference among light beams diffracted by many slits or grooves.



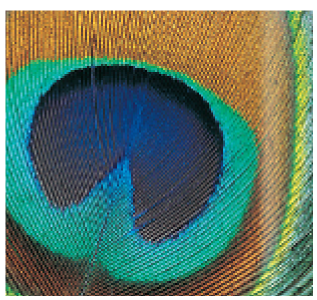


FIGURE 31.17 ▲
Diffraction from ridges in a peacock's feathers produces beautiful iridescent colors.

More common diffraction gratings are seen in reflective materials used in items such as costume jewelry. These materials have hundreds or thousands of close-together, tiny grooves that diffract light into a brilliant spectrum of colors. The pits on the reflective surface of an audio compact disc not only provide high-fidelity music but also diffract light spectacularly into its component colors. But long before the advent of these high-tech items, the feathers of birds were nature's diffraction gratings, as is beautifully illustrated in Figure 31.17. Similarly, the striking colors of opals come from layers of tiny silica spheres that act as diffraction gratings.

CONCEPT CHECK What did Young's experiment demonstrate?

31.5 Interference From Thin Films

Everyone who has seen soap bubbles or gasoline spilled on a wet street, as in Figure 31.18, has noticed the beautiful spectrum of colors reflected from them. Some types of bird feathers have colors that seem to change hue as the bird moves. ✔ **The colors seen in thin films are produced by the interference in the films of light waves of mixed frequencies.** The phenomenon in which the interference of light waves of mixed frequencies produces a spectrum of colors is known as **iridescence.**

A thin film, such as a soap bubble, has two closely spaced surfaces. Light that reflects from one surface may cancel light that reflects from the other surface. For example, the film may be just the right thickness in one place to cause the destructive interference of, say, blue light. If the film is illuminated with white light, then the light that reflects to your eye will have no blue in it. What happens when blue is taken away from white light? The answer is, the complementary color will appear. And for the cancellation of blue, we get yellow. So the soap bubble will appear yellow wherever blue is canceled.

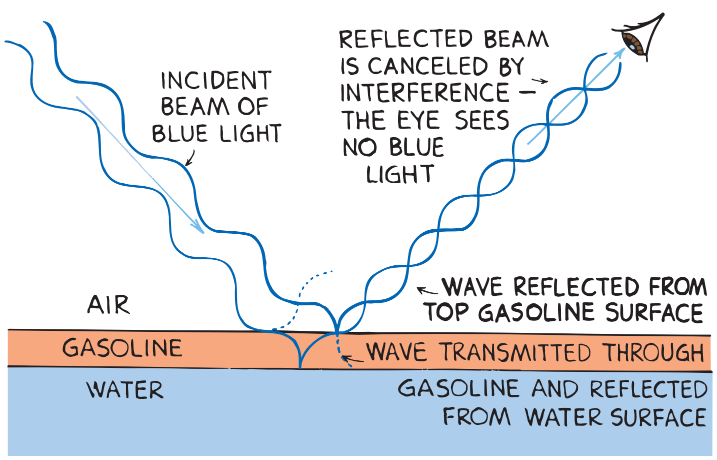
In a thicker part of the film, where green is canceled, the bubble will appear magenta. The different colors correspond to the cancellations of their complementary colors by different thicknesses of the film.

Figure 31.19 illustrates interference for a thin layer of gasoline on a layer of water. Light reflects from both the upper gasoline–air surface and the lower gasoline–water surface. Suppose that the incident beam is monochromatic blue, as in the illustration. If the gasoline layer is just the right thickness to cause cancellation of light of that wavelength, then the gasoline surface appears dark to the eye. On the other hand, if the incident beam is white sunlight, the gasoline surface appears yellow to the eye. Blue is subtracted from the white, leaving the complementary color, yellow.

FIGURE 31.18 ▲ The intriguing colors of gasoline on a wet street correspond to different thicknesses of the thin film.

think!

What color will reflect from a soap bubble in sunlight when its thickness is such that red light is canceled?
Answer: 31.5



◀ FIGURE 31.19 The thin film of gasoline is just the right thickness that monochromatic blue light reflected from the top surface of the gasoline is canceled by light of the same wavelength reflected from the water.

31.5 Interference From Thin Films

Key Term
iridescence

▶ **Teaching Tip** Mention the iridescent colors that appear to change with position in the feathers of some birds—peacocks, pigeons, starlings, etc.—and in soap bubbles and certain seashells. State that these colors are produced by interference.

▶ **Teaching Tip** Illustrate how colors reflect from gasoline on a wet street by sketching Figure 31.19 on the board. Note the 180° phase shift at each reflecting surface.

▶ **Teaching Tip** Emphasize the need for two surfaces for interference colors and why the film should be thin. (Recombination of “split” waves cannot occur when the reflected rays are widely displaced.)

Ask Why are interference colors not seen from gasoline spilled on a dry surface? *Without the smooth water beneath the film of gasoline, the lower surface of the gasoline would not be a smooth reflector.*

▶ **Teaching Tip** Another example of interference is that of the bluish tint of coated camera lenses. Camera lenses are coated to destroy doubly reflected light in a lens. Light that doubly reflects in a lens arrives at the film out of focus. All the wavelengths of light that are doubly reflected can't be destroyed by interference—not with a single thin film. But a film thickness of one-quarter the wavelength of yellow light will cancel the most predominant color in sunlight—yellow. So the sunlight you see reflected from a coated lens is deficient in yellow and appears blue.

Teaching Tip Note that the interference colors in Figures 31.18 and 31.20 are subtractive colors (magenta, cyan, yellow), showing that primary colors have been subtracted by the process of interference.

CONCEPT CHECK The colors seen in thin films are produced by the interference in the films of light waves of mixed frequencies.

Teaching Resources

- **Reading and Study Workbook**
- **Presentation*EXPRESS***
- **Interactive Textbook**

discover!

MATERIALS dark-colored mug, dishwashing detergent

EXPECTED OUTCOME Students will observe the swirling colors at the bottom of the film and the black appearance of the top of the film.

THINK The top of the film appears black when the film is thinner than 1/4 the wavelength of the shortest waves of visible light. At this point all of the light waves interfere destructively with one another.

FIGURE 31.20 ▶
Physicist and author Bob Greenler shows interference colors with *big* bubbles.

The beautiful colors reflected from some types of seashells are produced by interference of light in their thin transparent coatings. So are the sparkling colors from fractures within opals. Interference colors can even be seen in the thin film of detergent left when dishes are not properly rinsed.

Interference provides the principal method for measuring the wavelengths of light. Wavelengths of other regions of the electromagnetic spectrum are also measured with interference techniques. Extremely small distances (millionths of a centimeter) are measured with instruments called *interferometers,* which make use of the principle of interference. These instruments are sensitive enough to detect the displacement at the end of a long, several-centimeters-thick solid steel bar when you gently apply opposite twists to opposite ends with your hands. They are among the most accurate measuring instruments known.

CONCEPT CHECK **How are the colors seen in thin films produced?**

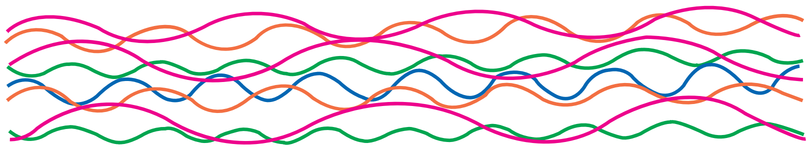
discover!

Where Did the Colors Go?

1. Dip a dark-colored coffee mug in dishwashing detergent and hold it sideways as if you were pouring from it.
2. Look at the reflected light from the soap film that covers its mouth.
3. What do you observe when the film becomes very thin—just before it pops?
4. **Think** Why does the top appear black when the film is very thin?

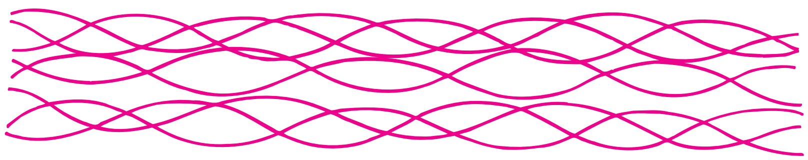
31.6 Laser Light

Light emitted by a common lamp is incoherent. In **incoherent** light, the crests and troughs of the light waves don't line up with one another (and there are many different frequencies as well). As shown in Figure 31.21, incoherent light is chaotic. Interference within a beam of incoherent light is rampant, and a beam spreads out after a short distance, becoming wider and wider and less intense with increased distance.



◀ **FIGURE 31.21**
Incoherent white light contains waves of many frequencies and wavelengths that are out of phase with one another.

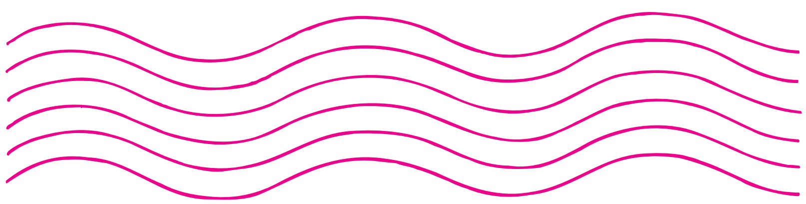
Even if a beam is filtered so that it is monochromatic (has a single frequency), as illustrated in Figure 31.22, it is still incoherent because the waves are out of phase and interfere with one another. The slightest differences in their directions result in a spreading with increased distance.



◀ **FIGURE 31.22**
Light of a single frequency and wavelength can still be out of phase.

Coherent Light A beam of light that has the same frequency, phase, and direction is said to be **coherent.** Figure 31.23 illustrates coherent light waves. There is no interference of waves within the beam. Only a beam of coherent light will not spread and diffuse.

Coherent light is produced by a **laser** (whose name comes from *light amplification by stimulated emission of radiation*).[31.6] ✓ **Laser light is emitted when excited atoms of a solid, liquid, or gas are stimulated to emit photons in phase.** Within a laser, a light wave emitted from one atom stimulates the emission of light from a neighboring atom so that the crests of each wave coincide. These waves stimulate the emission of others in cascade fashion, and a beam of coherent light is produced. This is very different from the random emission of light from atoms in common sources.



◀ **FIGURE 31.23**
Coherent light consists of identical waves that are all in phase.

31.6 Laser Light

Key Terms
incoherent, coherent, laser

Common Misconceptions
A laser is a high-efficiency device that emits more than just light.

A laser is an energy source that can put out more energy than it consumes.

FACT A laser emits only light and in fact does so quite inefficiently. A typical classroom laser is about 1% efficient.

▶ **Teaching Tip** Dispel the misconception that a laser is a powerful emitter of something other than light. Also dispel the notion that a laser is an efficient light source.

▶ **Teaching Tip** If you showed the spectrum of neon in Chapter 28, state that the frequency of light emitted from a helium–neon laser is just one of those many neon spectral lines.

▶ **Teaching Tip** Review the meanings of *monochromatic, destructive interference,* and *constructive interference*.

Demonstration

Give a laser show. Sprinkle chalk dust or smoke in a laser beam. An unforgettable presentation is directing a laser beam on a mirror fastened to a rubber membrane stretched over a radio loudspeaker. Do this to music and cover the darkened walls with a display of dancing Lissajous patterns.

▶ **Teaching Tip** Explain that the low pressure mixture of 85% helium and 15% neon in a helium–neon laser is subjected to a high voltage. This energizes (excites) the helium to a prolonged state of excitation. Before the helium radiates light it collides with neon atoms in the ground state, and transfers its energy to them. The amount of energy is just sufficient to excite neon to an otherwise difficult-to-achieve metastable state very close to the energy of the excited helium. The process continues and the population of excited neon atoms outnumbers that of neon atoms in the ground state. This inverted population is waiting to radiate its energy. When some neon atoms emit light, the radiation passes other excited neon atoms and triggers their de-excitation, exactly in phase with the stimulating radiation. Light parallel to the tube bounces from specially coated mirrors and the process cascades to produce a beam of coherent light.

CONCEPT CHECK Laser light is emitted when excited atoms of a solid, liquid, or gas are stimulated to emit photons in phase.

Teaching Resources

- Reading and Study Workbook
- Presentation*EXPRESS*
- Interactive Textbook

Go Online SCILINKS NSTA

For: Links on lasers
Visit: www.SciLinks.org
Web Code: csn – 3106

Operation of Lasers A laser is not a source of energy. It is simply a converter of energy, taking advantage of the process of stimulated emission to concentrate a certain fraction of the energy input (commonly much less than 1%) into a thin beam of coherent light. Like all devices, a laser can put out no more energy than it takes in.

In a helium-neon laser, which is shown in Figure 31.24, a high voltage applied to a mixture of helium and neon gas energizes helium atoms to a state of high energy. Before the helium can emit light, it gives up its energy by collision with neon, which is boosted to an otherwise hard-to-come-by matched energy state. Light emitted by neon stimulates other energized neon atoms to emit matched-frequency light. The process cascades, and a coherent beam of light is produced. The output remains steady because the helium is constantly reenergized.

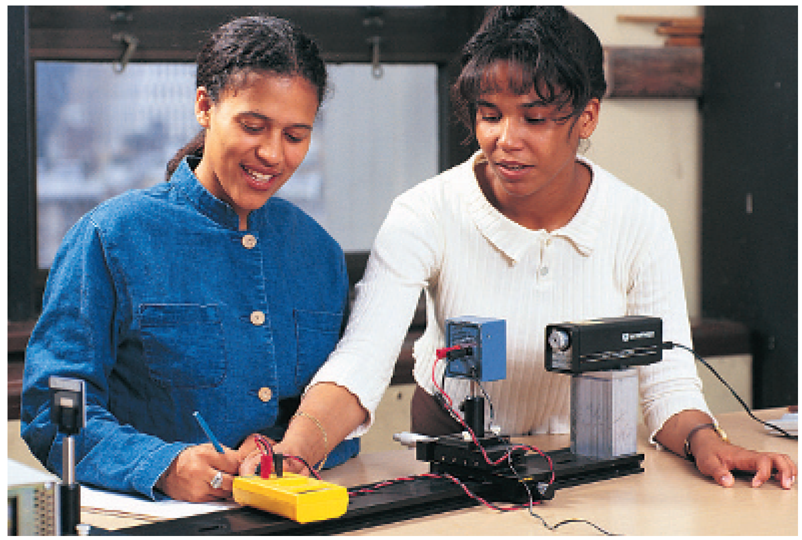


FIGURE 31.24 ▶ A helium-neon laser emits a steady output of coherent light.

780201 286526

FIGURE 31.25 ▲ A product code is read by laser light that reflects from the bar pattern and is converted to an electrical signal that is fed into a computer. The signal is high when light is reflected from the white spaces and low when reflected from a dark bar.

Applications of Lasers Lasers come in many types and have broad applications in diverse fields. Surveyors and construction workers use them as "chalk lines," surgeons use them as scalpels, and garment manufacturers use them as cloth-cutting saws. They are used to read product codes, like the one shown in Figure 31.25, into cash registers, to read the music and video signals in CDs and DVDs, and to read the bar code on the cover of your *Conceptual Physics* textbook. Lasers are now being used to cut metals, transmit information through optical fibers, and measure speeds of vehicles for law enforcement purposes. Scientists have even been able to use lasers as "optical tweezers" that can hold and move objects. A most impressive product of laser light is the hologram.

CONCEPT CHECK What causes a laser to emit light?

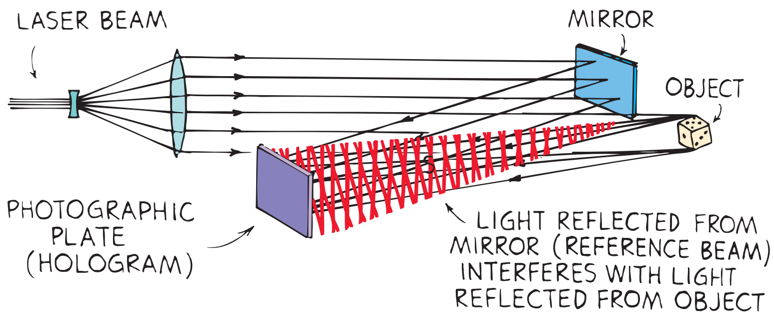
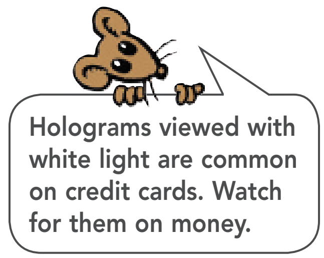


FIGURE 31.26
In this simplified arrangement for making a hologram, the laser light that exposes the photographic film is made up of two parts: one part is reflected from the object, and one part is reflected from the mirror.

31.7 The Hologram

A **hologram** is a three-dimensional version of a photograph that contains the whole message or entire picture in every portion of its surface. To the naked eye, it appears to be an imageless piece of transparent film, but on its surface is a pattern of microscopic interference fringes. Light diffracted from these fringes produces an image that is extremely realistic. Holograms are also difficult to reproduce—hence their use on credit cards.

Producing a Hologram **A hologram is produced by the interference between two laser light beams on photographic film.** The two beams are part of one beam. One part illuminates the object and is reflected from the object to the film. The second part, called the *reference beam,* is reflected from a mirror to the film, as shown in Figure 31.26. Interference between the reference beam and light reflected from the different points on the object produces a pattern of microscopic fringes on the film. Light from nearer parts of the object travels shorter paths than light from farther parts of the object. The different distances traveled will produce slightly different interference patterns with the reference beam. In this way information about the depth of an object is recorded.



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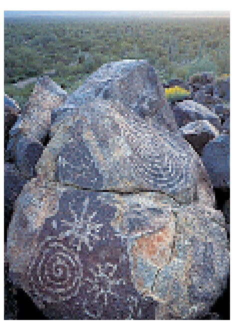

Spiky Stars All through the ages stars in the night sky have been drawn with pointed spikes. Ever wonder why? The reason doesn't have to do with the stars, which are point sources of light in the night sky, but rather with poor eyesight and diffraction. The surface of our eyes becomes scratched by a variety of causes and acts like a sort of diffraction grating. Instead of seeing point sources of light, we sometimes see spikes that may shimmer and twinkle due to temperature differences in the atmosphere. In a windy desert region where sandstorms are frequent, our corneas are even more scratched and we see more vivid star spikes. Stars don't really have pointed spikes. They just appear spiked because of scratches on the surfaces of our eyes.

31.7 The Hologram

Key Term
hologram

Common Misconception
A hologram is a mystery of science.

FACT A hologram is a pattern of microscopic fringes that forms a three-dimensional "photograph."

▶ **Teaching Tip** Using Figure 31.15, develop the idea of multiple slits for the diffraction grating. With a large diffraction grating, show the spectral lines of a gas discharge tube. Emphasize that there are really no physical lines where they appear to be and that the lines are virtual images of the glowing tube (just as they would be images of slits if a slit were being used).

▶ **Teaching Tidbit** Holograms are used in the currencies of several countries to deter counterfeiting.

▶ **Teaching Tip** When students understand how virtual images are produced by the diffraction grating, show the class a really sophisticated diffraction grating, not of vertical parallel lines in one dimension, but of microscopic swirls of lines in two dimensions—a hologram illuminated with a laser.

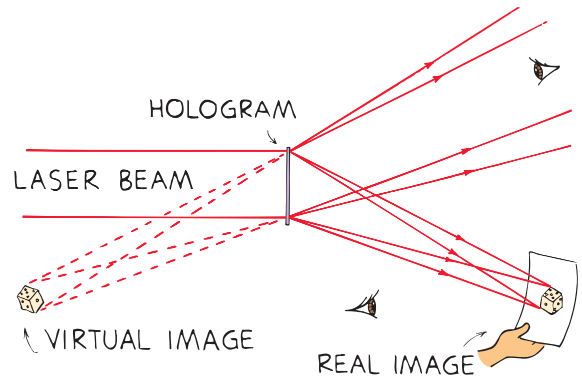

FIGURE 31.27 ▶
When a hologram is illuminated with coherent light, the diverging diffracted light produces a three-dimensional *virtual* image. Converging diffracted light produces a *real* image in front of the hologram.

Viewing a Hologram When light falls on a hologram, it is diffracted by the fringed pattern to produce wave fronts identical in form to the original wave fronts reflected by the object. The diffracted wave fronts produce the same effect as the original reflected wave fronts. As illustrated in Figure 31.27, when you look through a hologram, you see a three-dimensional virtual image. Looking through a hologram is like looking through a window. You refocus your eyes to see near and far parts of the image, just as you do when viewing a real object. Converging diffracted light produces a real image in front of the hologram, which can be projected on a screen. Since the image has depth, you cannot see near and far parts of the image in sharp focus for any single position on a flat screen. Parallax is evident when you move your head to the side and see down the sides of the object, or when you lower your head and look underneath the object. Holographic pictures appear to be three-dimensional, and therefore, are extremely realistic.

Interestingly enough, if the hologram is made on film, you can cut it in half and still see the entire image on each half. And you can cut one of the pieces in half again and again and see the entire image, just as you can put your eye to any part of a window to see outdoors. Every part of the hologram has received and recorded light from the entire object.

Even more interesting is holographic magnification. If holograms are made using short-wavelength light and viewed with light of a longer wavelength, the resulting image is magnified in the same proportion as the wavelengths. Holograms made with X-rays would be magnified thousands of times when viewed with visible light and appropriate viewing arrangements.

Light is interesting—especially when it is diffracted through the interference fringes of that supersophisticated diffraction grating, the hologram!

CONCEPT CHECK How is a hologram produced?

CONCEPT CHECK A hologram is produced by the interference between two laser light beams on photographic film.

Teaching Resources
- Reading and Study Workbook
- Transparency *75*
- Presentation*EXPRESS*
- Interactive Textbook

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31 REVIEW

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Concept Summary

- Huygens stated that light waves spreading out from a point source may be regarded as the overlapping of tiny secondary wavelets, and that every point on any wave front may be regarded as a new point source of secondary waves.

- The extent of diffraction depends on the relative size of the wavelength compared with the size of the obstruction that casts the shadow.
- Within an interference pattern, wave amplitudes may be increased, decreased, or neutralized.
- Young's interference experiment convincingly demonstrated the wave nature of light originally proposed by Huygens.
- The colors seen in thin films are produced by the interference in the films of light waves of mixed frequencies.
- Laser light is emitted when excited atoms of a solid, liquid, or gas are stimulated to emit photons in phase.
- A hologram is produced by the interference between two laser light beams on photographic film.

Key Terms

Huygens' principle *(p. 623)*
diffraction *(p. 625)*
monochromatic *(p. 629)*
diffraction grating *(p. 630)*
iridescence *(p. 631)*
incoherent *(p. 633)*
coherent *(p. 633)*
laser *(p. 633)*
hologram *(p. 635)*

think! Answers

31.2 Blue light has a shorter wavelength than most of the other wavelengths of visible light, so there's less diffraction. More details of the object will be visible under blue light.

31.4 If light of a variety of wavelengths were diffracted by the slits, dark fringes for one wavelength would be filled in with bright fringes for another, resulting in no distinct fringe pattern. If the path difference equals one-half wavelength for one frequency, it cannot also equal one-half wavelength for any other frequency. Different frequencies will "fill in" the fringes.

31.5 You will see the color cyan, which is the complementary color of red.

31 REVIEW

Teaching Resources

- Teacher*EXPRESS*
- Virtual Physics Lab *28*

31 ASSESS

Check Concepts

1. Each point on a wave front is a source of secondary wave fronts.
2. **a.** More
   b. Diffraction
3. It aids reception because the spreading causes the waves to reach more places.
4. It hinders the viewing because the spreading of waves blurs the image.
5. Yes, by destructive interference.
6. All waves; sound–beats; light–iridescence
7. Light and dark fringes are formed by overlapping monochromatic light waves.
8. Interference of light
9. A surface with many parallel slits to diffract light
10. A crest of one wave overlaps a trough of another.
11. Display of colors produced by interference
12. Its complementary color, blue
13. Interference of light reflected from gasoline and water surfaces
14. Device to measure tiny distances; light interference
15. It is coherent, monochromatic, and in phase.
16. No; this would violate the law of conservation of energy.
17. A 3-D photograph; interference between laser light beams
18. It is a 3-D image with limited parallax.

31 ASSESS

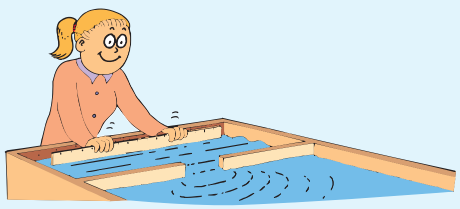
Check Concepts

Section 31.1

1. What is Huygens' principle?

Section 31.2

2. **a.** Waves spread out when they pass through an opening. Does spreading become more or less pronounced for narrower openings?
   b. What is this spreading called?



3. Does diffraction aid or hinder radio reception?
4. Does diffraction aid or hinder the viewing of images in a microscope?

Section 31.3

5. Is it possible for a wave to be canceled by another wave? Defend your answer.

Section 31.4

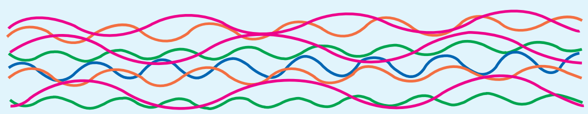
6. Does wave interference occur for waves in general, or only for light waves? Give examples to support your answer.
7. What was Thomas Young's discovery?
8. What is the cause of the fringes of light in Young's experiment?
9. What is a diffraction grating?

Section 31.5

10. What is required for part of the light reflected from a surface to be canceled by another part reflected from a second surface?
11. What is iridescence, and to what phenomenon is it related?
12. If a soap bubble is thick enough to cancel yellow by interference, what color will it appear if illuminated by white light?
13. Why is gasoline that is spilled on a wet surface so colorful?
14. What is an interferometer, and on what physics principle is it based?

Section 31.6

15. How does light from a laser differ from light from an ordinary lamp?



16. Can a laser put out more energy than is put in? (Would you have to know more about lasers to answer this question? Why?)

Section 31.7

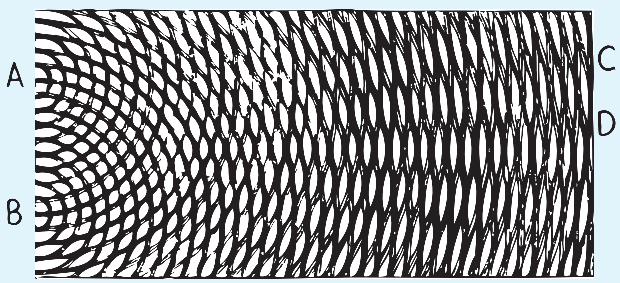
17. What is a hologram, and on what physics principle is it based?
18. How does the image of a hologram differ from that of a common photograph?

19. What would be the advantage of making holograms with X-rays?

Think and Rank

Rank each of the following sets of scenarios in order of the quantity or property involved. List them from left to right. If scenarios have equal rankings, then separate them with an equal sign. (e.g., A = B)

20. Thomas Young's drawing shows identical wave sources at points A and B. Points C and D mark regions of destructive interference where crests overlap troughs.



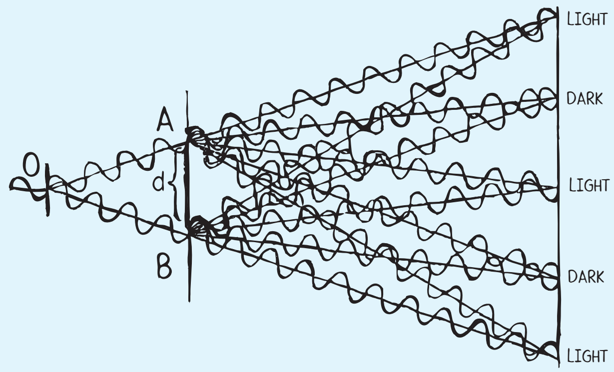
In the following scenarios, a change is made to wave sources A and B. Rank them by the distance between points C and D, from greatest to least.

(A) Distance between sources A and B is reduced to 0.9 as far.

(B) Distance between sources A and B is increased to 1.1 as far.

(C) Wavelength of waves is reduced to half.

21. Dark and light fringes on the screen are produced by interference. In the following scenarios, a change is made to either the light source or the spacing *d* between slits A and B. Rank them by the distance between fringes, from greatest to least.



(A) Slit spacing *d* between A and B is reduced to 0.9*d*.

(B) Slit spacing *d* between A and B is increased to 1.1*d*.

(C) Wavelength of light is doubled.

Think and Explain

22. Suppose the speakers at an open-air rock concert are pointed forward. You move about and notice that the sounds of female vocalists can be heard in front of the stage, but very little off to the sides. By comparison you notice that bass sounds can be heard quite well both in front and off to the sides. What is your explanation?

19. The image would be magnified in the same proportion as the wavelengths.

Think and Rank

20. A, B, C

21. C, A, B

Think and Explain

22. The sounds from a female vocalist are usually shorter wavelength and therefore do not diffract as well.

23. Diffraction is more pronounced for long waves.

24. Radio waves have much longer wavelengths.

25. The listener is walking through the "interference fringes" of sound.

26. Along a line perpendicular to and intersecting the line joining the two speakers

27. Farther apart because of its longer wavelength

28. Reflections from two closely spaced surfaces arrive out of phase and destructively interfere, leaving the complementary color. As the surfaces are viewed from different angles, different optical paths are presented to the eye, and different wavelengths are canceled to produce different complementary colors.

29. Light that passes through the double openings is part of the same wave front. The light that passes through the double openings is coherent.

30. Each color represents a certain "elevation" of the oil above the water surface.

31. No to both; changing the viewing angle or the thickness of the gasoline layer changes the path length in the gas and therefore another color would be seen.

31 ASSESS *(continued)*

23. In our everyday environment, diffraction is much more evident for sound waves than for light waves. Why is this so?

24. Why do radio waves diffract around buildings while light waves do not?

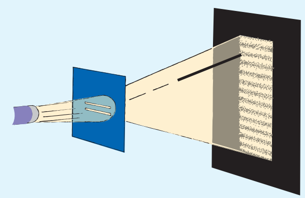
25. Suppose a pair of loudspeakers a meter or so apart emit pure tones of the same frequency and loudness. When a listener walks past in a path parallel to the line that joins the loudspeakers, the sound is heard to alternate from loud to soft. What is going on?

26. In the preceding question, suggest a path along which the listener could walk so as not to hear alternate loud and soft sounds.

27. When monochromatic light illuminates a pair of thin slits, an interference pattern is produced on a wall behind. How will the distance between the fringes of the pattern for red light differ from that for blue light?

28. Seashells, butterfly wings, and the feathers of some birds often change color as you look at them from different positions. Explain this phenomenon in terms of light interference.

29. When Thomas Young performed his interference experiment, monochromatic light passed through a single narrow opening before it reached the double openings. Explain why this made the fringes clear. (*Hint*: What would be the result if light reaching the double openings came from several different directions?)



30. If you notice the interference patterns of a thin film of oil or gasoline on water, you'll note that the colors form complete rings. How are these rings similar to the lines of equal elevation on a contour map?

31. Figure 31.19 shows destructive interference of blue light waves reflected from the top gasoline surface and from the top water surface. If white light is incident at the same angle, the eye sees yellow light. Would changing the viewing angle still produce yellow light? Would changing the thickness of the gasoline layer still show yellow? Defend your answers.

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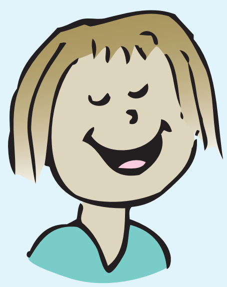
32. Suppose the thickness of a soap film is just right for canceling yellow light.
 a. What color does the eye see?
 b. Why will this color change when the surface is viewed at a grazing angle?

33. The interference colors seen in soap bubbles are not reds, greens, and blues, but instead are magentas, yellows, and cyans. Why?



34. The left column lists some colored objects. Match them to the various ways that light may produce that color from the choices in the right column.

a. yellow bananas	**1.** interference
b. blue sky	**2.** diffraction
c. rainbow	**3.** selective reflection
d. peacock feathers	**4.** refraction
e. soap bubble	**5.** scattering

Activity

35. Make some slides for a slide projector by sticking crumpled cellophane onto pieces of slide-sized polarizing material. Also try strips of cellophane tape, overlapping at different angles. (Experiment with different brands of tape.) Project the slides onto a large screen or white wall and rotate a second, slightly larger piece of polarizing material in front of the projector lens. The colors are vivid! Do this in rhythm with your favorite music, and you'll have your own light and sound show. Write a detailed description of how you put together your show.

More Problem-Solving Practice
Appendix F

32. a. Blue
b. The longer path through the film cancels longer wavelength light.

33. Destructive interference results in the *subtraction* of certain colors, leaving complementary colors to be seen.

34. a. 3
b. 5
c. 4
d. 2
e. 1

Activity

35. Have students perform their light shows for the class.

Teaching Resources
- Computer Test Bank
- Chapter and Unit Tests