CHAPTER 29

Light Waves

29.1 Huygens' Principle

29.2 Diffraction

29.3 Superposition and Interference

29.4 Thin-Film Interference

29.5 Polarization

29.6 Holography

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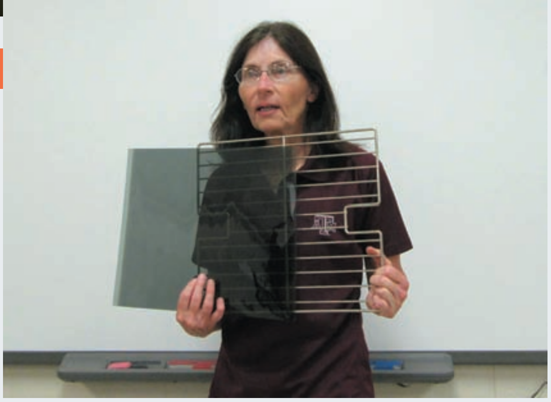


1 Robert Greenler shows interference colors with a *big* soap bubble. **2** This photo is a highly valued one for physics teachers Marshall Ellenstein and Helen Yan, who were in the Cal Tech parking lot discussing the Feynman diagrams on Feynman's van when Richard Feynman came by—and agreed to this pose. **3** New Zealander Jennie McKelvie shows wave behavior with a ripple tank. **4** Janie Head leads her class into a study of polarization by comparing how a rope shaken through the metal grating relates to light passing through a Polaroid.

After *Conceptual Physics* was first published in 1971, I met Marshall Ellenstein at a physics conference in Chicago. He was one of the first teachers to adopt the book that he had intended to write. Marshall asked if I would come to his home in Chicago for dinner with him and his wife. He also asked if I'd visit his classes in the high school where he taught. I agreed to both requests and we have been close friends ever since.

Marshall, now retired, was among Chicago's finest physics teachers. In addition to his passion for teaching physics, he's an accomplished magician and a prize winner in both jitterbug dancing and bridge playing. In his teaching he believes that physics is too exciting and relevant to everyday life not to be part of the educational mainstream. Because he possessed all the qualities that make for a great teacher, his physics classes were overflowing with students eager to learn. A term project at the time I visited was having each student produce a scrapbook of ten photographs that showed physics in daily life. The punch line, given well into the school term after all the photos were submitted, was that *any* photograph shows physics—that physics is *everywhere*. Even a blank all-white photo shows the reflection of whatever color of light is incident upon it. For Marshall's students physics wasn't something tucked away in books or on lab shelves.

Marshall never wrote his physics textbook. Instead, he pumped ideas to me continuously over the years, hence the many "Thanks to Marshall Ellenstein" at the bottoms of Practice Book pages and Next-Time Questions. Marshall edited video footage of my classroom lectures, earlier years at City College of San Francisco, and later years at the University of Hawaii, and has digitized these videos, which are now "video on demand" available to viewers using such electronic devices as a smart phone, iPad, or computer. Marshall has also posted "Hewitt drew it" screencasts on YouTube. Video and screencast listings are coded throughout this text. Less conspicuous are his many ideas within the textbook paragraphs and figures. In this chapter, for example, Marshall suggested the section on three-dimensional viewing and provided the computer-generated stereogram in Figure 29.41. He urged me to present holograms and helped me to tailor topics throughout the book.

Like many teachers, Marshall began physics with the study of light rather than mechanics, his experience telling him that light was a better hook for gaining initial student interest. We begin this chapter as Marshall did in his courses, with the wave nature of light.

29.1 Huygens' Principle

Throw a rock into a quiet pool, and waves appear along the surface of the water. Strike a tuning fork, and waves of sound spread in all directions. Light a match, and waves of light similarly expand in all directions. In 1678 a Dutch physicist, Christian Huygens, studied wave behavior and proposed that the wavefronts of light waves spreading out from a point source may be regarded as the overlapped crests of tiny secondary waves (Figure 29.2)—that wavefronts are made up of tinier wavefronts. This idea is called **Huygens' principle**:

> **Every point of a wavefront may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the waves.**

FIGURE 29.1
Water waves form concentric circles.

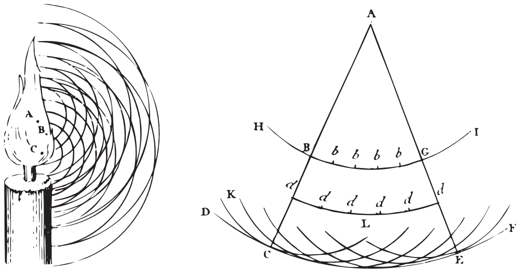


FIGURE 29.2
These drawings are from Huygens' book *Treatise on Light*. Light from A expands in wavefronts, every point of which behaves as if it were a new source of waves. Secondary wavelets starting at *b*, *b*, *b*, *b* form a new wavefront (*dddd*); secondary wavelets starting at *d*, *d*, *d*, *d* form still another new wavefront (DCEF).

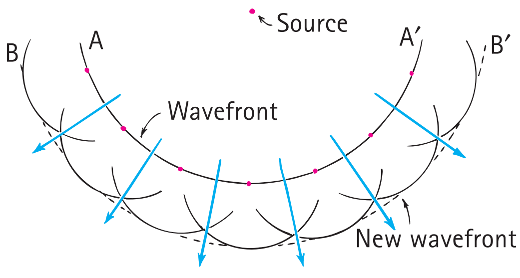


FIGURE 29.3

INTERACTIVE FIGURE

Huygens' principle applied to a spherical wavefront.

Consider the spherical wavefront in Figure 29.3. We can see that if all points along the wavefront AA′ are sources of new wavelets, then a short time later the new overlapping wavelets will form a new surface, BB′, which may be regarded as the envelope of all the wavelets. In the figure we show only a few of the infinite number of wavelets from a few secondary point sources along AA′ that combine to produce the smooth envelope BB′. As the wave spreads, a segment appears less curved. Very far from the original source, the waves nearly form a plane—as do waves from the Sun, for example. A Huygens wavelet construction for plane wavefronts is shown in Figure 29.4. We see the laws of reflection and refraction illustrated via Huygens' principle in Figure 29.5.

FIGURE 29.4

INTERACTIVE FIGURE

Huygens' principle applied to a plane wavefront.

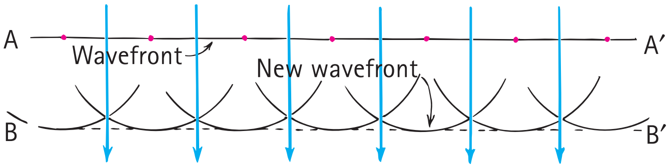


FIGURE 29.5

Huygens' principle applied to (a) reflection and (b) refraction. Notice that rays and wavefronts are perpendicular to each other.

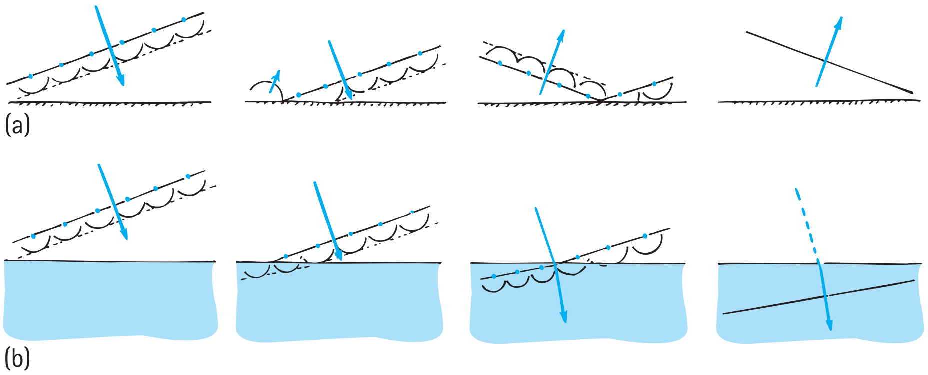
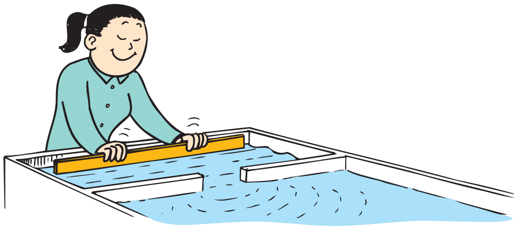


FIGURE 29.6

The oscillating meterstick makes plane waves in the tank of water. Water oscillating in the opening acts as a source of waves. Water diffracts through the opening.



Plane waves can be generated in water by successively dipping a horizontally held straightedge, such as a meterstick, into the surface (Figure 29.6). The photographs in Figure 29.7 are top views of a ripple tank in which plane waves are incident upon openings of various sizes (the straightedge is not shown). In (a), where the opening is wide, we see the plane waves continue through the opening without

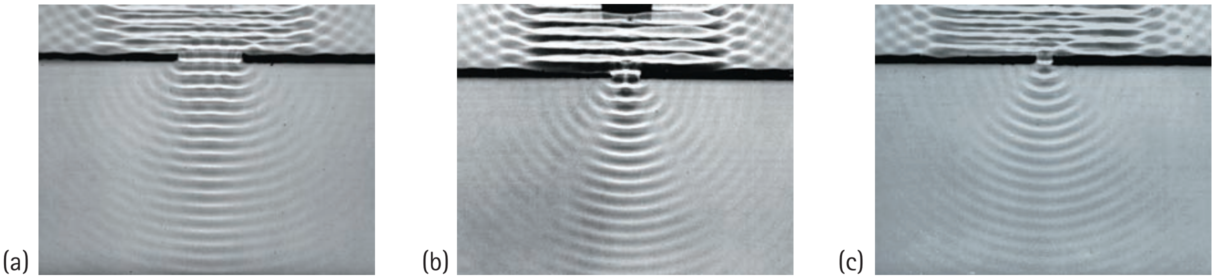


FIGURE 29.7

Plane waves passing through openings of various sizes. The smaller the opening, the greater the bending of the waves at the edges—in other words, the greater the diffraction.

change—except at the corners, where the waves are bent into the shadow region, as predicted by Huygens' principle. As the width of the opening is narrowed, as in (b), less and less of the incident wave is transmitted, and the spreading of waves into the shadow region becomes more pronounced. When the opening is small compared with the wavelength of the incident wave, as in (c), the truth of Huygens' idea that every part of a wavefront can be regarded as a source of new wavelets becomes quite apparent. As the waves are incident upon the narrow opening, the water sloshing up and down in the opening is easily seen to act as a "point" source of the new waves that fan out on the other side of the barrier. We say that the waves are *diffracted* as they spread into the shadow region.

29.2 Diffraction

In Chapter 28, we learned that light can be bent from its ordinary straight-line path by reflection and by refraction, and now we learn another way in which light bends. Any bending of light by means other than reflection and refraction is called *diffraction*. **Diffraction** is the bending of light as it passes the edge of an object, creating a fuzzy edge. It also occurs when a wave passes through an aperture. The diffraction of plane water waves shown in Figure 29.7 occurs for all kinds of waves, including light waves.

If someone in another room calls you, the sound seems to be coming from the doorway (unless you have very thin walls).

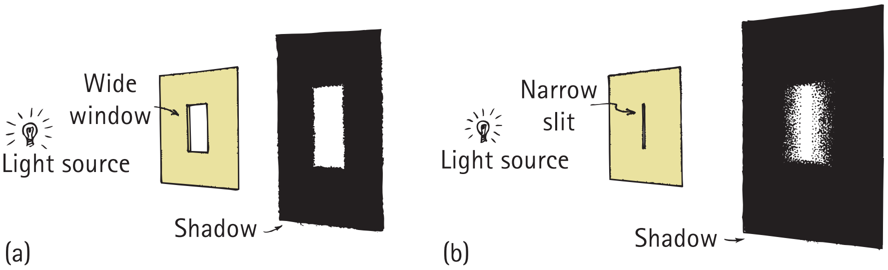


FIGURE 29.8
INTERACTIVE FIGURE
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(a) Light casts a sharp shadow with some fuzziness at its edges when the opening is large compared with the wavelength of the light.
(b) When the opening is very narrow, diffraction is more apparent and the shadow is fuzzier.

When light passes through an opening that is large compared with the wavelength of light, it casts a shadow such as the one shown in Figure 29.8a. We see a rather sharp boundary between the light and dark areas of the shadow. But if we pass light through a thin razor slit in a piece of opaque cardboard, we see that the light diffracts (Figure 29.8b). The sharp boundary between the light and dark areas disappears, and the light spreads out like a fan to produce a bright area that fades into darkness without sharp edges. The light is diffracted.

A graph of the intensity distribution for diffracted light through a single thin slit appears in Figure 29.9. Because of diffraction, there is a gradual increase in the light intensity rather than an abrupt change from dark to light. A photodetector sweeping across the screen would sense a gradual change from no light to maximum light. (Actually, there are slight fringes of intensity on either side of the main pattern; we will see shortly that these are evidence of interference that is more pronounced with a double slit or multiple slits.)

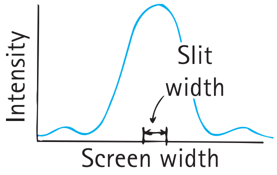


FIGURE 29.9
Graphic interpretation of diffracted light through a single thin slit.

Diffraction is not confined to narrow slits or to openings in general but can be seen for all shadows. On close examination, even the sharpest shadow is blurred slightly at the edge. When the light is of a single color (monochromatic), diffraction can produce *diffraction fringes* at the edge of the shadow, as in Figure 29.10. In white light, the fringes merge together to create a fuzzy blur at the edge of a shadow.

FIGURE 29.10
Diffraction fringes are evident in the shadows of monochromatic (single-frequency) laser light. These fringes would be filled in by multitudes of other fringes if the source were white light.

SCREENCAST: Diffraction

The amount of diffraction depends on the wavelength of the wave compared with the size of the obstruction that casts the shadow. Longer waves diffract more. They're better at filling in shadows, which is why the sounds of foghorns are low-frequency long waves—to fill in any "blind spots." Likewise for radio waves of the standard AM broadcast band, which are very long compared with the size of most objects in their path. The wavelengths of AM radio waves range from 180 to 550 meters, and the waves readily bend around buildings and other objects that might otherwise obstruct them. A long-wavelength radio wave doesn't "see" a relatively small building in its path, but a short-wavelength radio wave does. The radio waves of the FM band range from 2.8 to 3.4 meters and don't bend very well around buildings. This is one of the reasons FM reception is often poor in localities where AM comes in loud and clear. In the case of radio reception, we don't wish to "see" objects in the path of radio waves, so diffraction is not a bad thing.

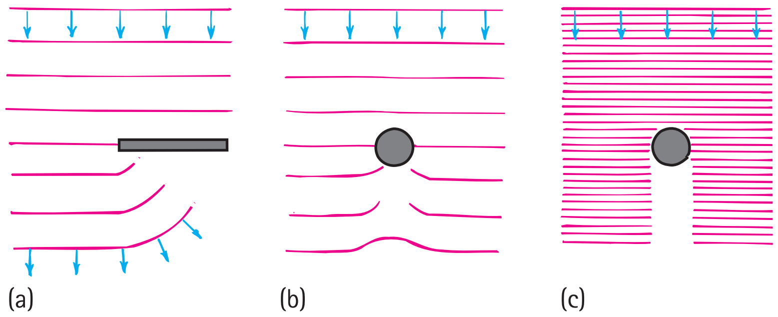


FIGURE 29.11
(a) Waves tend to spread into the shadow region.
(b) When the wavelength is about the size of the object, the shadow is soon filled in.
(c) When the wavelength is short relative to the object's size, a sharper shadow is cast.

Diffraction is not so nice for viewing very small objects with a microscope. If the size of an object is about the same as the wavelength of light, diffraction blurs the image. If the object is smaller than the wavelength of light, no structure can be seen. The entire image is lost due to diffraction. No amount of magnification or perfection of microscope design can overcome this fundamental diffraction limit.

To minimize this problem, microscopists can illuminate tiny objects with electron beams rather than with light. Relative to light waves, electron beams have extremely short wavelengths. *Electron microscopes* take advantage of the fact that all matter has wave properties: A beam of electrons has a wavelength shorter than those of visible light. In an electron microscope, electric and magnetic fields, rather than optical lenses, are used to focus and magnify images.

The fact that smaller details can be seen better with shorter wavelengths is neatly employed by the dolphin in scanning its environment with ultrasound. The echoes of long-wavelength sound give the dolphin an overall image of objects in its surroundings. To examine more detail, the dolphin emits sound of shorter wavelengths. As discussed in Chapter 20, the dolphin has always done naturally what physicians are now able to do with ultrasonic imaging devices.

Diffraction occurs when a wave passes through an aperture or by the edge of an object.

CHECK POINT

Why does a microscopist use blue light rather than white light to illuminate objects being viewed?

CHECK YOUR ANSWER

There is less diffraction with shorter-wavelength blue light, so the microscopist sees more detail (just as a dolphin beautifully investigates fine detail in its environment by the echoes of ultra-short wavelengths of sound).

29.3 Superposition and Interference

When two waves interact, the amplitude of the resulting wave is the sum of the amplitudes of the two individual waves. This is called the principle of **superposition**. This phenomenon is generally described as **interference** (as discussed in Chapters 19 and 20). Constructive and destructive interference are reviewed in Figure 29.12. We see that the superposition of a pair of identical waves in phase with each other produces a wave of the same frequency but twice the amplitude. If the waves are exactly one-half wavelength out of phase, their superposition results in complete cancellation. If they are out of phase by other amounts, partial cancellation occurs.

SCREENCAST: Interference of Light

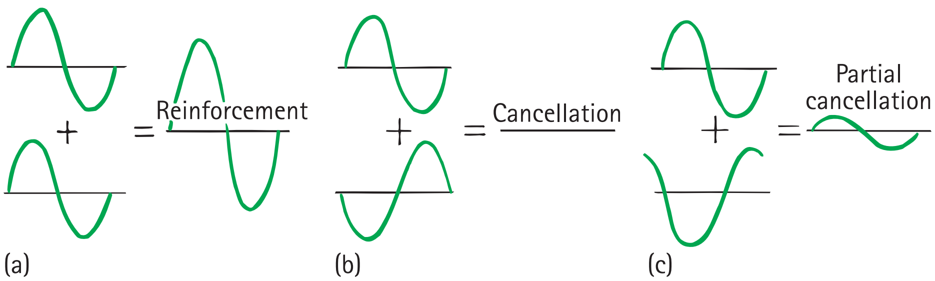


FIGURE 29.12
Wave interference.

The interference of water waves is a common sight, as shown in Figure 29.13. In some places, crests overlap crests; in other places, crests overlap troughs of other waves.

FIGURE 29.13
Interference of water waves.

Under more carefully controlled conditions, interesting patterns are produced by a pair of wave sources placed side by side (Figure 29.14). The surface of water in shallow tanks (ripple tanks similar to Jennie's in the third chapter-opening photo) is tapped at a certain frequency in two places while the patterns produced are photographed from above. Note that areas of constructive and destructive interference extend as far as the right-side edges of the ripple tanks, where the number of these regions and their size depend on the distance between the wave sources and on the wavelength (or frequency) of the waves. Interference is not restricted to easily seen water waves but is a property of all waves.

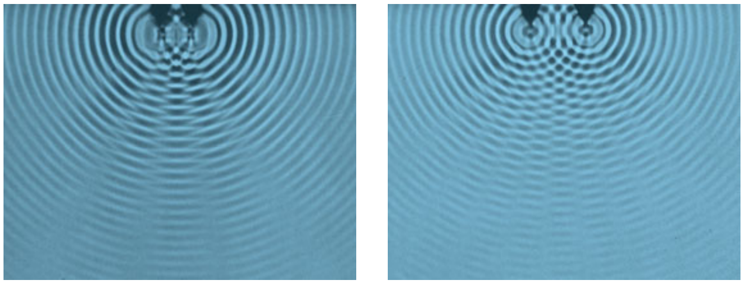
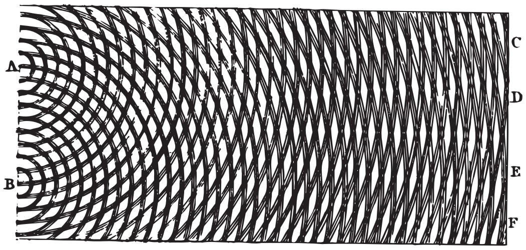


FIGURE 29.14
Interference patterns of overlapping waves from two vibrating sources.

In 1801, the wave nature of light was convincingly demonstrated when British physicist and physician Thomas Young performed his now-famous interference

FIGURE 29.15

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. Constructive interference occurs where crests overlap crests or troughs overlap troughs. The letters C, D, E, and F mark regions of destructive interference.



experiment.[1] Young found that light directed through two closely spaced pinholes recombines to produce fringes of brightness and darkness on a screen behind. The bright fringes form when a crest from the light wave through one hole and a crest from the light wave through the other hole arrive at the screen at the same time. The dark fringes form when a crest from one wave and a trough from the other arrive at the same time. Figure 29.15 shows Young's drawing of the pattern of superimposed waves from the two sources. When his experiment is performed with two closely spaced slits instead of pinholes, the fringe patterns are straight lines (Figure 29.17).

FIGURE 29.16

Bright fringes occur when waves from both slits arrive in phase; dark areas result from the overlapping of waves that are out of phase.

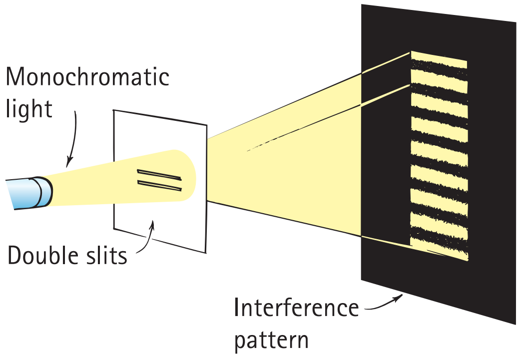


FIGURE 29.17

INTERACTIVE FIGURE

When monochromatic light passes through two closely spaced slits, a striped interference pattern is produced.

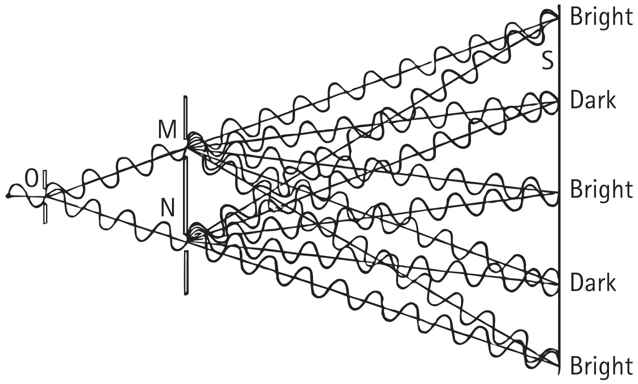
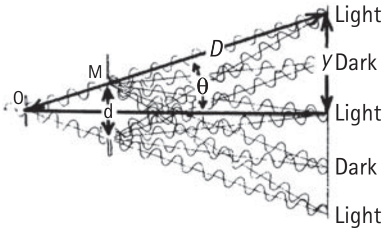


FIGURE 29.18

INTERACTIVE FIGURE

Light from O passes through slits M and N and produces an interference pattern on the screen S.

We see in Figure 29.18 how the series of bright and dark lines results from the different path lengths from the slits to the screen.[2] For the central bright fringe, the paths from the two slits are the same length and so the waves arrive in phase



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[1] Thomas Young read fluently at the age of 2; by 4, he had read the Bible twice; by 14, he knew eight languages. In his adult life, he was a physician and a scientist, contributing to an understanding of fluids, work and energy, and the elastic properties of materials. He was the first person to make progress in deciphering Egyptian hieroglyphics. No doubt about it—Thomas Young was a bright guy!

[2] In lab, you may determine the wavelength of light using measurements based on Figure 29.18. The equation for the first off-center interference maximum from two or more slits is

$$\lambda = d \sin \theta$$

where λ is the wavelength of light being diffracted, d is the distance between adjacent slits, and θ is the angle between lines to the central fringe of light and the first off-center constructive interference fringe. From the diagram, $\sin \theta$ is the ratio of distance y to distance D, where y is the distance on the screen between the central fringe of light and the first constructive-interference fringe on either side, and D is the distance from the fringe to the slits (which, in practice, is much greater than shown here).

and reinforce each other. The dark fringes on either side of the central fringe result from one path being longer (or shorter) by one-half wavelength, so that the waves arrive half a wavelength out of phase. The other sets of dark fringes occur where the paths differ by odd multiples of one-half wavelength: 3/2, 5/2, and so on.

In performing this double-slit experiment, suppose we cover one of the slits so that light passes through only a single slit. Then the light will fan out and illuminate the screen to form a simple diffraction pattern, as discussed earlier (Figures 29.8b and 29.9). If we cover the other slit and allow light to pass through only the slit just uncovered, we get the same illumination on the screen, but displaced somewhat because of the difference in slit location. If we didn't know better, we might expect that with both slits open, the pattern would simply be the sum of the single-slit diffraction patterns, as suggested in Figure 29.19a. But this doesn't happen. Instead, the pattern formed is one of alternating light and dark bands, as shown in Figure 29.19b. We have an interference pattern. Interference of light waves does not, by the way, create or destroy light energy; it merely redistributes it.

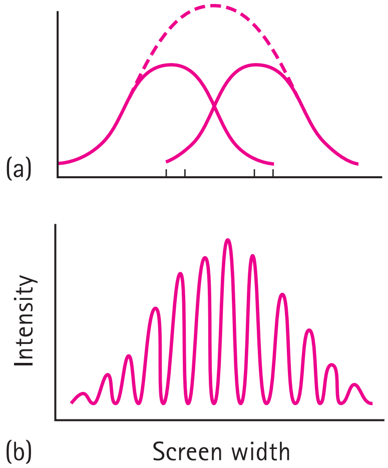

FIGURE 29.19
The light that diffracts through each of the double slits does not form a superposition of intensities as suggested in (a). The intensity pattern, because of interference, is as shown in (b).

CHECK POINT

1. **If the double slits were illuminated with monochromatic (single-frequency) red light, would the fringes be more widely or more closely spaced than if they were illuminated with monochromatic blue light?**
2. **Why is it important that monochromatic light be used?**

CHECK YOUR ANSWERS

1. More widely spaced. Can you see in Figure 29.18 that a slightly longer—and therefore a slightly more displaced—path from entrance slit to screen would result for the longer waves of red light?
2. If light of various 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 you haven't seen this, be sure to ask your instructor to demonstrate it.

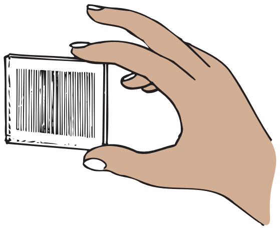

FIGURE 29.20
A diffraction grating may be used in place of a prism in a spectrometer.

Interference patterns are not limited to single and double slits. A multitude of closely spaced slits makes up a *diffraction grating*. These devices, like prisms, disperse white light into colors. Whereas a prism separates the colors of light by refraction, a diffraction grating separates colors by interference. These are used in devices called *spectrometers*, which we will discuss in Chapter 30. Diffraction gratings are ruled with tiny grooves and spread white light into bands of color. They are common in some kinds of costume jewelry and in "party glasses" (Figure 29.21). Tiny grooves in the feathers of some birds disperse beautiful colors. Colors created by diffraction are especially vivid on the reflective surfaces of DVDs.

FIGURE 29.21
Lamps of a chandelier as seen through diffraction-grating party glasses.

29.4 Thin-Film Interference

Vivid colors are also produced by the double reflection of light from the top and bottom surfaces of thin films. Colors range from fringes of monochromatic light to the brilliant array of colors seen in soap bubbles.

Single-Color Thin-Film Interference

A simple demonstration of light interference can be set up with a monochromatic light source and a couple pieces of glass. A sodium-vapor lamp is a good source of monochromatic light. The two pieces of glass are placed one atop the other, as shown in Figure 29.22. A very thin piece of paper is placed between the plates at one edge to provide a very thin wedge-shaped film of air between the plates. If the eye is in a position to see the reflected image of the lamp, the image will not be continuous but will be made up of dark and bright bands.

The cause of these bands is the interference between the waves reflected from the glass on the top and bottom surfaces of the air wedge, as shown in the exaggerated view in Figure 29.23. The light reflecting from point P comes to the eye by two different paths. In one of these paths, the light is reflected from the top of the air wedge; in the other path, it is reflected from the lower side. If the eye is focused on point P, both rays reach the same place on the retina of the eye. But these rays have traveled different distances and may meet in phase or out of phase, depending on the thickness of the air wedge—that is, on how much farther one ray has traveled than the other. When we examine the entire surface of the glass, we see alternate dark and bright regions—the dark portions, where the air thickness is just right to produce destructive interference, and the bright portions, where the air wedge is just the proper amount thinner or thicker to result in the reinforcement of light. So the dark and bright bands are caused by the interference of light waves reflected from the two sides of the thin film.[3]

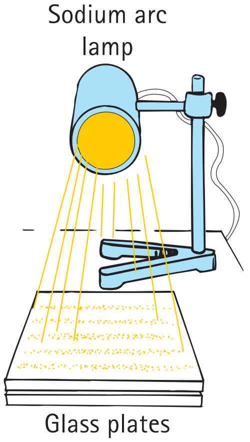

FIGURE 29.22
Interference fringes produced when monochromatic light is reflected from two plates of glass that have an air wedge between them.

SCREENCAST: Interference of Colors

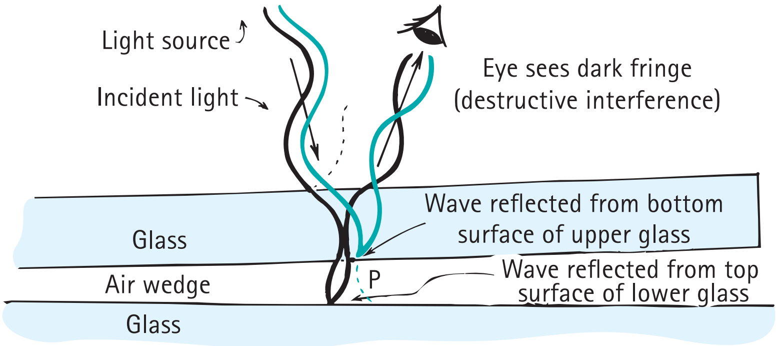

FIGURE 29.23
Reflection from the upper and lower surfaces of a “thin film of air.” (One wave is drawn in black to show how it is out of phase with the blue wave upon reflection.)

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[3] Phase shifts at some reflecting surfaces also contribute to interference. For simplicity and brevity, our concern with this topic will be limited to this footnote. In short, when light in a medium is reflected at the surface of a second medium in which the speed of light is lower (when there is a greater index of refraction), there is a 180° phase shift (that is, half a wavelength). However, no phase shift occurs when the second medium is one that transmits light at a higher speed (and has a lower index of refraction). In our air-wedge example, no phase shift occurs for reflection at the upper glass–air surface, and a shift does occur at the lower air–glass surface. So, at the apex of the air wedge where the thickness approaches zero, the phase shift produces cancellation, and the wedge is dark. Likewise with a soap film so thin that its thickness is appreciably smaller than the wavelength of light. This is why parts of a film that are extremely thin appear black. Waves of all frequencies are canceled.

If the surfaces of the glass plates are perfectly flat, the bands are uniform. But if the surfaces are not perfectly flat, the bands are distorted. The interference of light provides an extremely sensitive method for testing the flatness of surfaces. Surfaces that produce uniform fringes are said to be optically flat—this means that surface irregularities are small relative to the wavelength of visible light (Figure 29.24).

When a lens that is flat on top and has slight convex curvature on the bottom is placed on an optically flat plate of glass and illuminated from above with monochromatic light, a series of light and dark rings is produced. This pattern is known as *Newton's rings* (Figure 29.25). These light and dark rings are the same kinds of fringes observed with plane surfaces. This is a useful testing technique in polishing precision lenses.

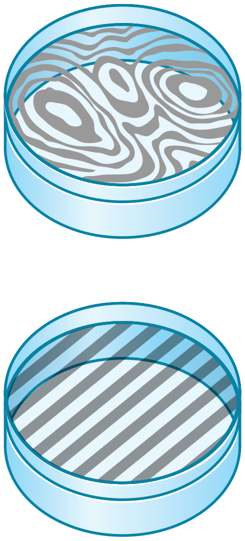

FIGURE 29.24
Optical flats used for testing the flatness of surfaces. The straight fringes indicate optical flatness.

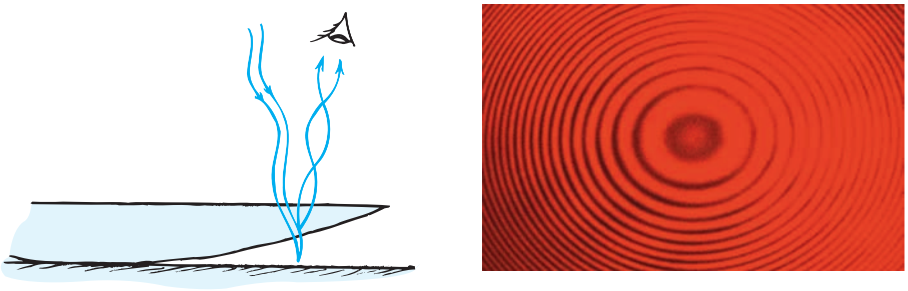

FIGURE 29.25
Newton's rings.

CHECK POINT

How would the spacings between Newton's rings differ when illuminated by red light and by blue light?

CHECK YOUR ANSWER

The rings would be more widely spaced for the longer-wavelength red light than for the shorter waves of blue light. Do you see the geometric reason for this?

Interference Colors

We have all noticed the beautiful spectrum of colors reflected from a soap bubble or from gasoline on a wet street. These colors are produced by the *interference* of light waves. This phenomenon is often called *iridescence* and is observed in thin transparent films.

Soap-bubble colors result from the interference of reflected light from the inside and outside surfaces of the soap film. When a color is canceled, what you see is its complementary color.

A soap bubble appears iridescent in white light when the thickness of the soap film is about the same as the wavelength of light. Light waves reflected from the outer and inner surfaces of the film travel different distances. When illuminated by white light, the film may be just the right thickness at one place to cause the destructive interference of, say, red light. When red light is subtracted from white light, the mixture left will appear as the complementary color of red, which is cyan. At another place, where the film is thinner, a different color may be canceled by interference, and the light seen will be its complementary color.

The same thing happens to gasoline on a wet street (Figure 29.26). Light reflects from both the upper gasoline surface and the lower gasoline–water surface. If the thickness of the gasoline is such that it cancels blue, as the figure suggests, then the gasoline surface appears yellow to the eye. This is because the blue is subtracted from the white, leaving the complementary color, yellow. The different colors, then, correspond to different thicknesses of the thin film, providing a vivid "contour map" of microscopic differences in surface "elevations." Over a wider field of view, different colors can be seen, even if the thickness of the gasoline film is uniform. This is due to the apparent thickness of the film: Light reaching the eye from different parts of the surface is reflected at different angles and traverses different thicknesses. If the light is incident at a grazing angle, for example, the ray transmitted to the gasoline's lower surface travels a longer distance. Longer waves are canceled in this case, and different colors appear.

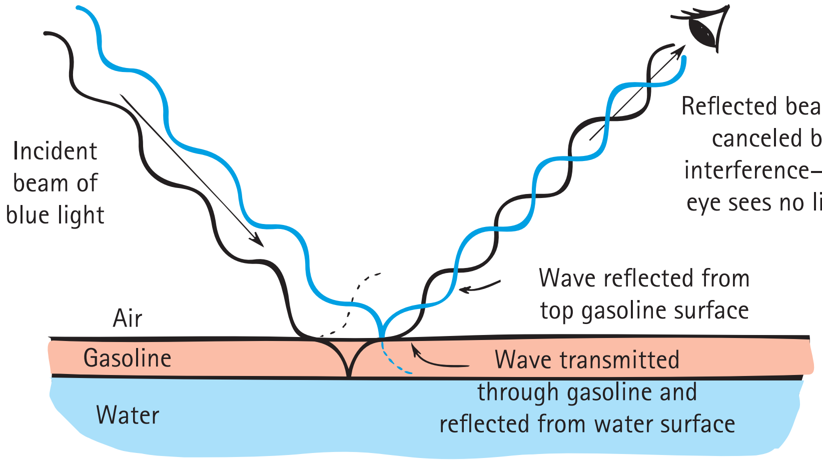

FIGURE 29.26
The thin film of gasoline is just the right thickness to cancel the reflections of blue light from the top and bottom surfaces. When the incident beam is white light, the eyes see yellow. If the film were thinner, perhaps shorter-wavelength violet would be canceled. (Again, one wave is drawn in black to show how it is out of phase with the blue wave upon reflection.)

Dishes washed in soapy water and poorly rinsed have a thin film of soap on them. Hold such a dish up to a light source so that *interference colors* can be seen. Then turn the dish to a new position, keeping your eye on the same part of the dish, and the color will change. Light reflecting from the bottom surface of the transparent soap film is canceling light reflecting from the top surface of the soap film. Light waves of different wavelengths are canceled for different angles. Interference colors are best seen in soap bubbles (Figure 29.27). You'll notice that these colors are predominantly cyan, magenta, and yellow due to the subtraction of primary red, green, and blue, or other colors of a single wavelength.

Interference provides a way to measure the wavelength of light and other electromagnetic radiation. It also makes it possible to measure extremely small distances with great accuracy. Instruments called *interferometers*, which use the principle of interference, are the most accurate instruments known for measuring small distances.

FIGURE 29.27
The magenta seen in Emily's soap bubbles is due to the cancellation of green light. What primary color is canceled to produce cyan?

VIDEO: Soap Bubble Interference

PRACTICING PHYSICS

Do this physics experiment at your kitchen sink. Dip a dark-colored coffee cup (dark colors make the best background for viewing interference colors) in dishwashing detergent and then hold it sideways and look at the reflected light from the soap film that covers its mouth. Swirling colors appear as the soap flows down to form a wedge that grows thicker at the bottom. Swirls of color appear that correspond to various thicknesses of the thin soapy film. The top becomes thinner, so thin that it appears black. Whatever its wavelength, light reflecting from the inner surface reverses phase, rejoins light reflecting from the outer surface, and cancels. The film soon becomes so thin it pops.

29.5 Polarization

Interference and diffraction provide the best evidence that light is wavelike. As we learned in Chapter 19, waves can be either longitudinal or transverse. Sound waves are longitudinal, which means that the vibratory motion is *along* the direction of wave travel. But when we shake a taut rope, the vibratory motion traveling along the rope is perpendicular, or *transverse*, to the rope. Both longitudinal and transverse waves exhibit interference and diffraction effects. Are light waves, then, longitudinal or transverse?

Polarization of the light waves demonstrates that they are transverse. Only transverse waves can be polarized. Consider the taut rope being swung in Figure 29.28. A transverse wave travels along the rope in one plane. We say that such a wave is *plane-polarized*,[4] meaning that the waves traveling along the rope are confined to a single plane. If we shake the rope up and down, we produce a vertically plane-polarized wave. If we shake it from side to side, we produce a horizontally plane-polarized wave.

A single vibrating electron can emit an electromagnetic wave that is plane-polarized. The plane of polarization will match the vibrational direction of the electron and is the plane of the electric field's vibration. A vertically accelerating electron, then, emits light that is vertically polarized, while a horizontally accelerating electron emits light that is horizontally polarized (Figure 29.29).

A common light source—such as an incandescent lamp, a fluorescent lamp, or a candle flame—emits light that is unpolarized. This is because there is no preferred vibrational direction for the accelerating electrons that are emitting the light. The planes of vibration might be as numerous as the accelerating electrons that produce them. A few planes are represented in Figure 29.30a. We can represent all these planes by radial lines (Figure 29.30b) or, more simply, by vectors in two mutually perpendicular directions (Figure 29.30c), as if we had resolved all the vectors of Figure 29.30b into horizontal and vertical components. This simpler schematic represents unpolarized light. Polarized light would be represented by a single vector.

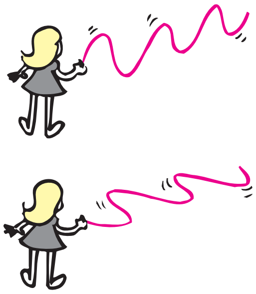

FIGURE 29.28
A vertically plane-polarized wave and a horizontally plane-polarized wave.

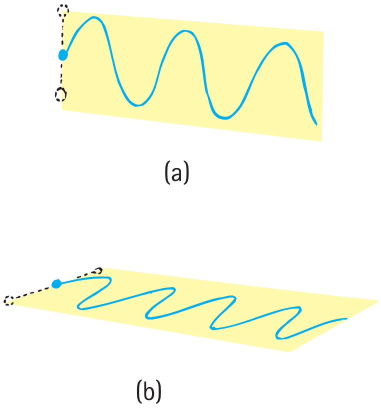

FIGURE 29.29
(a) A vertically plane-polarized wave from a charge vibrating vertically. (b) A horizontally plane-polarized wave from a charge vibrating horizontally.

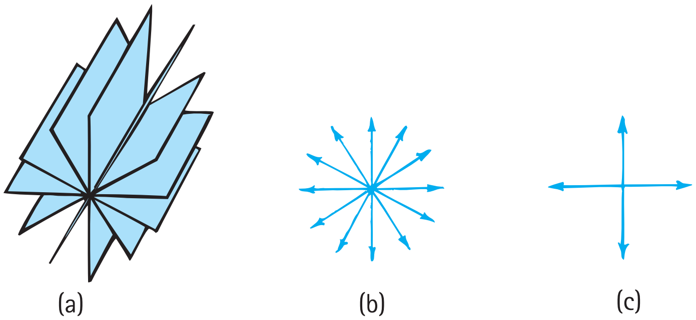

FIGURE 29.30
Representations of plane-polarized waves. The three representations show the electric part of the electromagnetic wave.

All transparent crystals of a noncubic natural shape have the property of transmitting light of one polarization differently from light of another polarization. Certain crystals[5] not only divide unpolarized light into two internal beams polarized at right angles to each other but also strongly absorb one beam while transmitting the other (Figure 29.31). Tourmaline is one such common crystal, but, unfortunately, the transmitted light is colored. Herapathite, however, does the job without discoloration. Microscopic crystals of herapathite are embedded between cellulose sheets in uniform alignment and are used in making Polaroid filters. Some Polaroid sheets consist of certain aligned molecules rather than tiny crystals.[6]

If you look at unpolarized light through a Polaroid filter, you can rotate the filter in any direction and the light will appear unchanged. But if you are looking

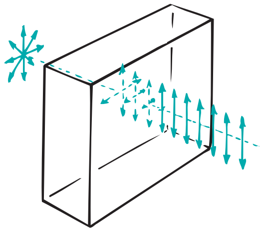

FIGURE 29.31
One component of the incident unpolarized light is absorbed, resulting in emerging polarized light.

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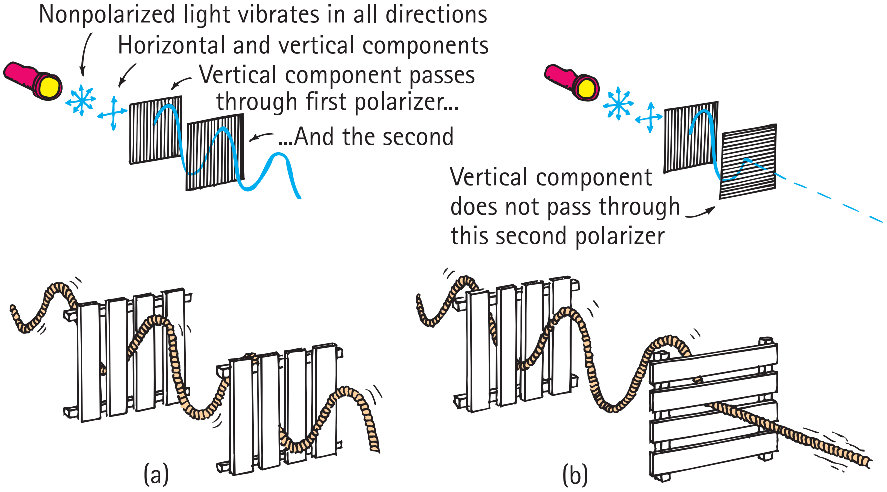
[4] Light may also be circularly polarized and elliptically polarized, which are combinations of transverse polarizations. But we will not study these cases.

[5] Called *dichroic*.

[6] The molecules are polymeric iodine in a sheet of polyvinyl alcohol or polyvinylene.

FIGURE 29.32
A rope analogy illustrates the effect of crossed Polaroids.



SCREENCAST: Polarization of Light

at polarized light and you rotate the filter, you can progressively cut off more and more of the light until it is entirely blocked out. An ideal Polaroid will transmit 50% of the incident unpolarized light. That 50% is, of course, polarized. When two Polaroids are arranged so that their polarization axes are aligned, light will be transmitted through both (Figure 29.32a). If their axes are at right angles to each other (in this case we say the filters are *crossed*), no light penetrates the pair (Figure 29.32b). (Actually, some light of the shorter wavelengths does get through, but not to any significant degree.) When Polaroids are used in pairs like this, the first one is called the *polarizer* and the second one is called the *analyzer*.[7]

Much of the light reflected from nonmetallic surfaces is polarized. The glare from glass or water is a good example. Except for perpendicular incidence, the reflected ray contains more vibrations parallel to the reflecting surface, whereas the transmitted beam contains more vibrations at right angles to the vibrations of reflected light (Figure 29.35). This is analogous to skipping flat rocks off the surface of a pond. When the rocks hit with their faces parallel to the surface, they easily reflect, but if they hit with their faces tilted to the surface, they "refract" into the water. The glare from reflecting surfaces can be appreciably diminished with the use of Polaroid sunglasses. The polarization axes of the lenses are vertical because most glare reflects from horizontal surfaces.

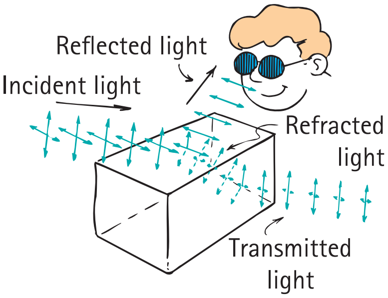


FIGURE 29.33
Most glare from nonmetallic surfaces is polarized. Note how components of incident light parallel to the surface are reflected and how components perpendicular to the surface pass through the surface into the medium.

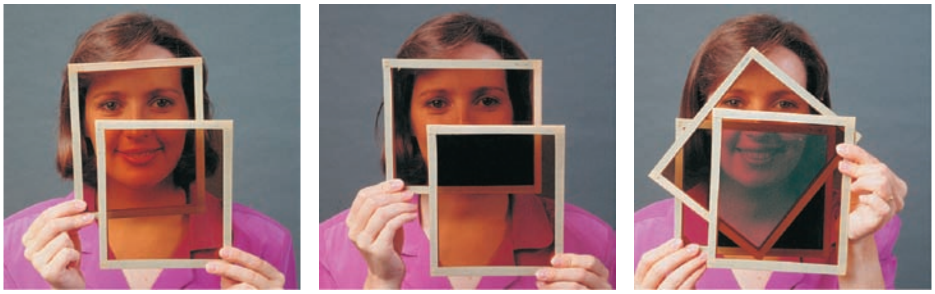


FIGURE 29.34
Light is transmitted when the axes of the Polaroids are aligned (a), but absorbed when Ludmila rotates one so that the axes are at right angles to each other (b). When she inserts a third Polaroid at an angle between the crossed Polaroids, light is again transmitted (c). Why? (For the answer—after you have given this some thought—see Appendix D, "Vector Applications.")

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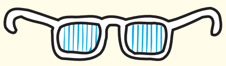
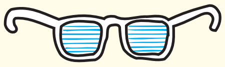
[7] In a common Polaroid filter, long-chain molecules are oriented with their axis perpendicular to the polarizing axis, and they preferentially *absorb* (rather then transmit) light polarized along their length, much like an antenna absorbs radio waves. Such filters are in contrast to the rope-through-the-fence analogy of Figure 29.32. For either type of filter, the point to learn is that the transmitted and absorbed wave components are at right angles to each other.

CHECK POINT

Which pair of eyeglasses is best suited for automobile drivers? (The polarization axes are shown by the straight lines.)



(a)



(b)

(c)

CHECK YOUR ANSWER

Glasses (a) are best suited because the vertical axis blocks horizontally polarized light, which constitutes most of the glare from horizontal surfaces. Glasses (c) are suited for viewing 3-D movies.

FIGURE 29.35

Polaroid sunglasses block out horizontally vibrating light. When the lenses overlap at right angles, no light gets through.

Three-Dimensional Viewing

Vision in three dimensions depends primarily on the fact that both eyes give their impressions simultaneously (or nearly so), with each eye viewing the scene from a slightly different angle. This is *parallax*, which is evident when you view an upright finger at arm's length and see how it appears to shift position from left to right in front of the background as you alternately close each eye. With both eyes open you tend to look somewhat "around" your finger. If you view the pair of drawings in Figure 29.36 in such a way that the left eye looks at the left view while the right eye looks at the right view, you will see a stereo view with depth. The drawings illustrate a stereo view of the crystal structure of ice.

Snowflakes that appear in a single plane in the pair of drawings of Figure 29.37 are seen to be in different planes when viewed stereoscopically.

Polarization occurs only for transverse waves. In fact, it is an important way of determining whether a wave is transverse or longitudinal.

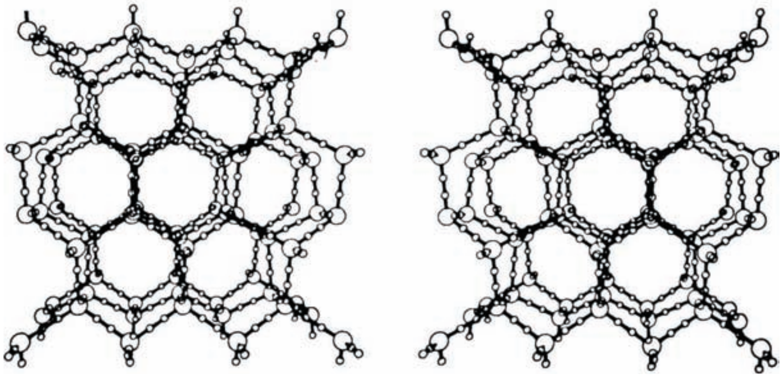


FIGURE 29.36

The crystal structure of ice in stereo. You'll see depth when your brain combines the views of your left eye looking at the left figure and your right eye looking at the right figure. To accomplish this, focus your eyes for distant viewing before looking at this page. Without changing your focus, look at the page, and each figure will appear double. Then adjust your focus so that the two inside images overlap to form a central composite image. Practice makes perfect. (If you instead *cross* your eyes to overlap the figures, near and far are reversed!)

VIDEO: Polarized Light and 3-D Viewing

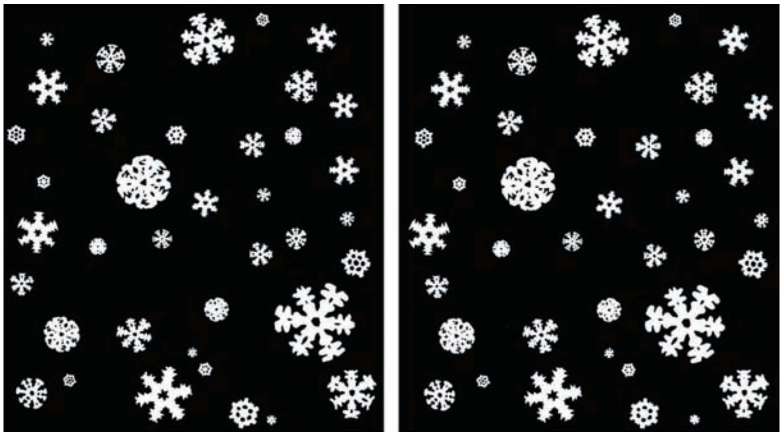
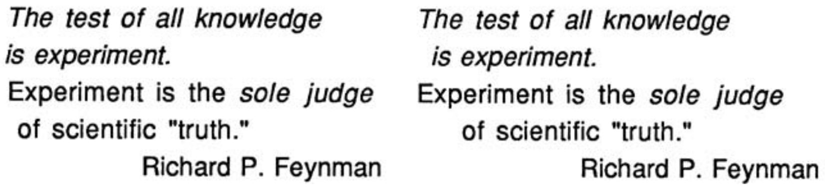


FIGURE 29.37

A stereo view of snowflakes. View these images in the same way as Figure 29.36.

FIGURE 29.38
A stereoscopic viewer.

The handheld stereoscopic viewer familiar to your grandparents (Figure 29.38) simulates the effect of depth. In this device, there are two photographic transparencies (or slides) taken from slightly different positions. When they are viewed at the same time, the arrangement is such that the left eye sees the scene as photographed from the left, and the right eye sees it as photographed from the right. As a result, the objects in the scene sink into relief in correct perspective, giving apparent depth to the picture. The device is constructed so that each eye sees only the proper view. There is no chance for one eye to see both views. If you remove the slides from the hand viewer and project each view on a screen by slide projector (so that the views are superimposed), a blurry picture results.



The test of all knowledge is experiment.
Experiment is the *sole judge* of scientific "truth."
Richard P. Feynman

The test of all knowledge is experiment.
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Richard P. Feynman

FIGURE 29.39
With your eyes focused for distant viewing, the second and fourth lines appear to be farther away; if you cross your eyes, the second and fourth lines appear closer.

This is because each eye sees both views simultaneously. This is where Polaroid filters come in. If you place the Polaroids in front of the projectors so that they are at right angles to each other, and you view the polarized image with polarized glasses of the same orientation, each eye will see the proper view as with the stereoscopic viewer (Figure 29.39). You then will see an image in three dimensions.

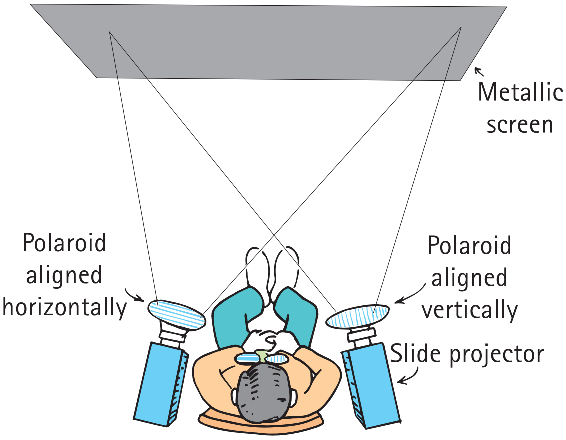

FIGURE 29.40
A 3-D show using Polaroids. The left eye sees only polarized light from the left projector, the right eye sees only polarized light from the right projector, and both views merge in the brain to produce depth.

Depth is also seen in computer-generated stereograms, as in Figure 29.41. Here the slightly different patterns are not obvious in a casual view. Use the procedure for viewing the earlier stereo figures. Once you've mastered the viewing technique, head for the local mall and check the variety of stereograms in posters and books.

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- Watch for autostereoscopy, 3-D without Polaroid glasses. The system relies on lenticular lenses that project a slightly different image to each eye, creating the illusion of depth.

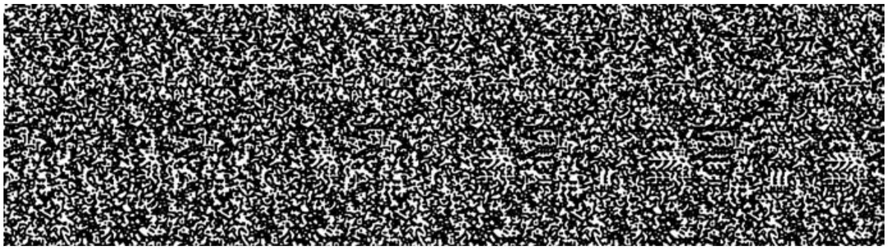


FIGURE 29.41
A computer-generated stereogram.

29.6 Holography

Perhaps the most exciting illustration of interference is the **hologram**, a two-dimensional photographic plate produced with laser light that allows you to see a faithful reproduction of a scene in three dimensions. The hologram was invented and named by Dennis Gabor in 1947, 10 years before lasers were invented. In Greek, *holo* means "whole" and *gram* means "message" or "information." Thus a hologram contains the whole message or entire picture. With proper illumination, the image is so realistic that you can actually look around the corners of objects in the image and see the sides.

In ordinary photography, a lens is used to form an image. Light reflected from each point on the object is directed by the lens only to a corresponding point on the film or photoreceptor. In the case of holography, however, no image-forming lens is used. Instead, each point of the object being "photographed" reflects light to the *entire* photographic plate, so every part of the plate is exposed with light reflected from every part of the object. It is important that the light used to make a hologram be of a single frequency and all parts exactly in phase: It must be *coherent*. If, for example, white light were used, the diffraction fringes for one frequency would be washed out by those of other frequencies. Only a laser can easily produce such light. (We will treat lasers in detail in Chapter 30.) Holograms are made with laser light but can be seen with regular light, as attested to by the hologram on your credit card or on some kinds of money.

Light is truly fascinating—especially when it is diffracted into interference fringes in a hologram. Look for detailed information about holograms on the Internet.

fyi

- Holographic optical elements that appear to float in front of an aircraft windshield help pilots in navigation. The same is featured on some models of automobiles. Medical doctors use 3-D holographic scans to make measurements without invasive surgery. The list of applications grows. Watch for a holographic TV in your future!

For instructor-assigned homework, go to www.masteringphysics.com MP

SUMMARY OF TERMS (KNOWLEDGE)

Huygens' principle Every point on a wavefront may be considered the source of secondary wavelets that spread out in all directions with a speed equal to the speed of propagation of the waves.

Diffraction The bending of light that passes near the edge of an object or through a narrow slit, causing the light to spread.

Superposition The overlapping and combining of waves.

Interference The result of superposing different waves, usually of the same wavelength. Constructive interference results from crest-to-crest reinforcement; destructive interference results from crest-to-trough cancellation. The interference of selected wavelengths of light produces colors known as *interference colors*.

Polarization The alignment of the transverse electric vibrations of electromagnetic radiation. Such waves of aligned vibrations are said to be *polarized*.

Hologram A two-dimensional microscopic interference pattern that shows three-dimensional optical images.

READING CHECK QUESTIONS (COMPREHENSION)

29.1 Huygens' Principle

1. According to Huygens, how does every point on a wavefront behave?
2. Will plane waves incident upon a small opening in a barrier fan out on the other side or continue on as plane waves?

29.2 Diffraction

3. Is diffraction more pronounced through a small opening or through a large opening?
4. For an opening of a given size, is diffraction more pronounced for a longer wavelength or for a shorter wavelength?
5. Which more easily diffracts around buildings: AM or FM radio waves? Why?

29.3 Superposition and Interference

6. Is interference restricted to only some types of waves, or does it occur for all types of waves?
7. What aspect of light did Thomas Young demonstrate in his famous light experiment?

29.4 Thin-Film Interference

8. What accounts for the light and dark bands that are produced when monochromatic light reflects from a glass plate atop another glass plate?
9. What is meant by saying that a surface is *optically flat*?
10. What is the cause of Newton's rings?
11. What produces iridescence?
12. What causes the spectrum of colors seen in gasoline splotches on a wet street? Why aren't these splotches seen on a dry street?
13. What accounts for the different colors in either a soap bubble or a layer of gasoline on water?
14. Why are interference colors primarily cyan, magenta, and yellow?

29.5 Polarization

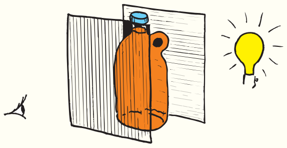
15. What phenomenon distinguishes longitudinal waves from transverse waves?
16. How does the direction of polarization of light compare with the direction of vibration of the electron that produces it?
17. Why will light pass through a pair of Polaroids when the axes are aligned but not when the axes are at right angles to each other?
18. How much ordinary light will an ideal Polaroid transmit?
19. When *ordinary* light is incident at an oblique angle upon water, what can you say about the *reflected* light?
20. Is parallax evident when you close one eye?
21. Does parallax underlie the depth perceived in stereo views?
22. Would the viewer perceive depth if the images being projected in Figure 29.40 were identical?
23. What role do polarization filters play in 3-D projection?

29.6 Holography

24. How does a hologram differ from a conventional photograph?

THINK AND DO (HANDS-ON APPLICATION)

25. With a razor blade, cut a slit in a card and look at a light source through it. You can vary the size of the opening by bending the card slightly. See the interference fringes? Try this experiment with two closely spaced slits.
26. Next time you're in the bathtub, froth up the soapsuds and notice the colors of highlights from the illuminating light overhead on each tiny bubble. Notice that different bubbles reflect different colors, due to the different thicknesses of soap film. If a friend is bathing with you, compare the different colors that each of you see reflected from the same bubbles. You'll see that they're different: What you see depends on your point of view!
27. When wearing Polaroid sunglasses, look at the glare from a nonmetallic surface, such as a road or body of water. Tip your head from side to side and see how the glare intensity changes as you vary the magnitude of the electric vector component aligned with the polarization axis of the glasses. Also notice the polarization of different parts of the sky when you hold the sunglasses in your hand and rotate them.
28. Place a source of white light on a table in front of you. Then place a sheet of Polaroid in front of the source, a bottle of corn syrup in front of the sheet, and a second sheet of Polaroid in front of the bottle. Look through the Polaroid sheets that sandwich the syrup and view spectacular colors as you rotate one of the sheets.



THINK AND EXPLAIN (SYNTHESIS)

29. Why can sunlight that illuminates Earth be approximated by plane waves, whereas the light from a nearby lamp cannot?
30. In our everyday environment, diffraction is much more evident for sound waves than for light waves. Why is this so?
31. Why do radio waves diffract around buildings but light waves do not?
32. How are interference fringes of light analogous to the varying intensity that you hear as you walk past a pair of speakers that are emitting the same sound?
33. By how much should a pair of light rays from a common source differ in distance traveled to produce destructive interference?
34. Light illuminates two closely spaced thin slits and produces an interference pattern on a screen behind. For which color of light—yellow or green—will the distance between the fringes be greater?
35. A double-slit arrangement produces interference fringes for yellow sodium light. Should red light or blue light be used to produce narrower-spaced fringes?

36. When the reflected path from one surface of a thin film is one full wavelength different in length from the reflected path from the other surface and no phase change occurs, will the result be destructive interference or constructive interference?
37. When the reflected path from one surface of a thin film is one-half wavelength different in length from the reflected path from the other surface and no phase change occurs, will the result be destructive interference or constructive interference?
38. Suppose you place a diffraction grating in front of a camera lens and take a picture of illuminated streetlights. What will you expect to see in your photograph?
39. What happens to the distance between interference fringes if the separation between two slits is increased?
40. Why is Young's experiment more effective with slits than with the pinholes he first used?
41. In which of these is color formed by refraction: flower petals, rainbows, soap bubbles? By selective reflection? By thin-film interference?
42. The colors of peacocks and hummingbirds are the result not of pigments but of ridges in the surface layers of their feathers. By what physical principle do these ridges produce colors?
43. The colored wings of many butterflies are due to pigmentation, but in others, such as the Morpho butterfly, the colors do not result from any pigmentation. When the wing is viewed from different angles, the colors change. How are these colors produced?
44. Why do the iridescent colors seen in some seashells (such as abalone shells) change as the shells are viewed from various positions?
45. When dishes are not properly rinsed after washing, different colors are reflected from their surfaces. Explain.
46. Why are interference colors more apparent for thin films than for thick films?
47. Will the light from two very close stars produce an interference pattern? Explain.
48. If you notice the interference patterns of a thin film of oil or gasoline on water, you'll see that the colors form complete rings. How are these rings similar to the lines of equal elevation on a contour map?
49. Because of wave interference, a film of oil on water in sunlight is seen to be yellow to observers directly above in an airplane. What color of light transmits through the oil (that would be seen by a scuba diver directly below)?
50. For the Hubble Telescope, which light—red, green, blue, or ultraviolet—is better for seeing fine details of distant astronomical objects?
51. Polarized light is a part of nature, but polarized sound is not. Why?
52. Why will an ideal Polaroid filter transmit 50% of incident nonpolarized light?
53. Why may an ideal Polaroid filter transmit anything from zero to 100% of incident polarized light?
54. What percentage of light is transmitted by two ideal Polaroids, one on top of the other with their polarization axes aligned? With their axes at right angles to each other?
55. How can you determine the polarization axis for a single sheet of Polaroid (especially if you're at the edge of a lake)?
56. Why do Polaroid sunglasses reduce glare, whereas nonpolarized sunglasses simply cut down the total amount of light reaching the eyes?
57. To remove the glare of light from a polished floor, should the axis of a Polaroid filter be horizontal or vertical?
58. Most of the glare from nonmetallic surfaces is polarized, with the axis of polarization parallel to the axis of the reflecting surface. Would you expect the polarization axis of Polaroid sunglasses to be horizontal or vertical? Why?
59. How can a single sheet of Polaroid film be used to show that the sky is partially polarized? (Interestingly enough, unlike humans, bees and many insects can discern polarized light and use this ability for navigation.)
60. Why did practical holography have to await the advent of the laser?
61. Which of these is most central to holography: interference, selective reflection, refraction, or all of these?

THINK AND DISCUSS (EVALUATION)

62. When white light diffracts upon passing through a thin slit, as in Figure 29.8b, different color components diffract by different amounts so that a rainbow of colors appears at the edge of the pattern. Which color is diffracted through the greatest angle? Which color through the smallest angle?
63. Which will give wider-spaced fringes in a double-slit experiment: red light or violet light? (Let Figure 29.18 guide your thinking.)
64. Which will give wider-spaced fringes: a double-slit experiment in air or in water? (Let Figure 29.18 guide your thinking.)
65. If the path-length difference between two identical and coherent beams is two wavelengths when they arrive on a screen, will they produce a dark or a bright spot?
66. Which will produce more widely spaced fringes of light when passed through a diffraction grating: light from a red laser or light from a green laser?
67. The digital displays of watches and other devices are normally polarized. What related problem can occur when you are wearing Polaroid sunglasses?
68. Light will not pass through a pair of Polaroid sheets when they are aligned perpendicularly. However, if a third Polaroid is sandwiched between the two with its alignment halfway between the alignments of the other two (that is, with its axis making a 45° angle with each of the other two alignment axes, as in Figure 29.34), some light does get through. Why?