29 Light Waves

2


3


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.

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 and said it was the book that he intended writing. Marshall asked if I'd 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 very 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 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. Physics wasn't something tucked away in books or on lab shelves with Marshall's students.

Marshall never wrote his textbook on physics. 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, which are featured in the Videos listings at the ends of chapters throughout this book. 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 treat holograms and helped me to tailor topics all 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 with his courses, with the wave nature of light.

Huygens' Principle

Throw a rock in 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 can 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.

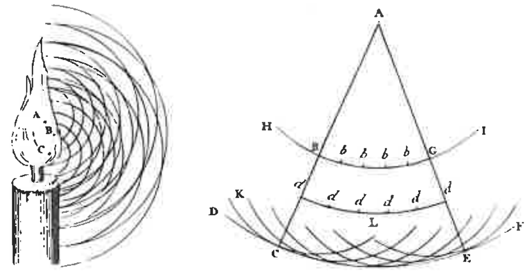


FIGURE 29.2
These drawings are from Huygens' book *Treatise on Light.* Light from A expands in wavefronts, every point of which behaves as if it were a new source of waves. Secondary wavelets starting at *b,b,b,b* form a new wavefront (*d,d,d,d*); secondary wavelets starting at *d,d,d,d* form still another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

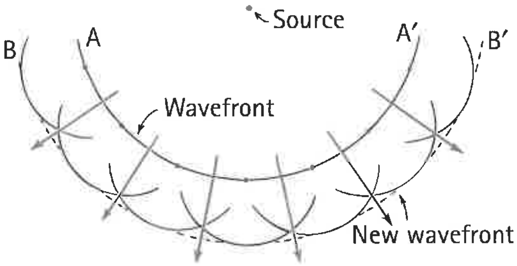


FIGURE 29.3
INTERACTIVE FIGURE
Huygens' principle applied to a spherical wavefront.

Consider the spherical wave front in Figure 29.3. We can see that if all points along the wavefront AA′ are sources of new wavelets, a short time later the new overlapping wavelets will form a new surface, BB′, which can 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.

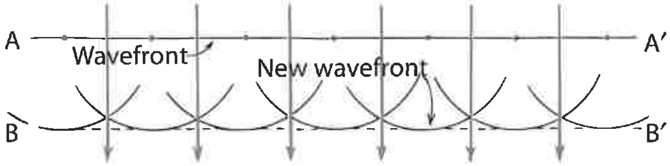


FIGURE 29.4
INTERACTIVE FIGURE
Huygens' principle applied to a plane wavefront.

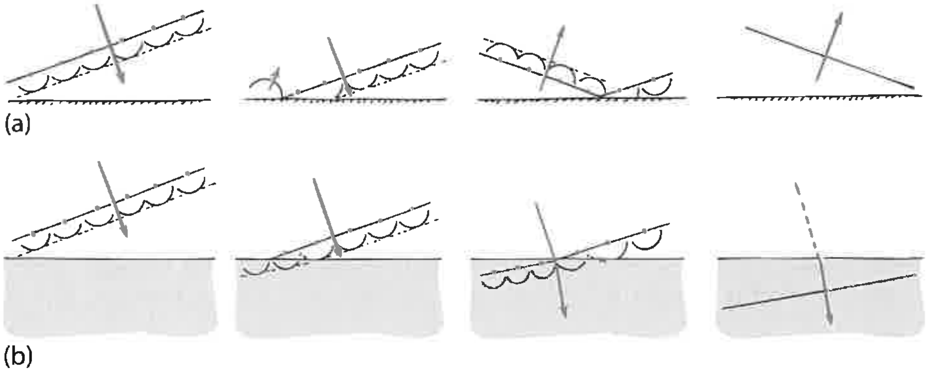


FIGURE 29.5
Huygens' principle applied to (a) reflection and (b) refraction. Notice that rays and wavefronts are perpendicular to each other.

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 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.

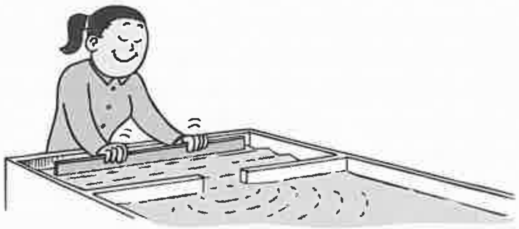


FIGURE 29.6

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.

Diffraction

In the previous chapter, 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.

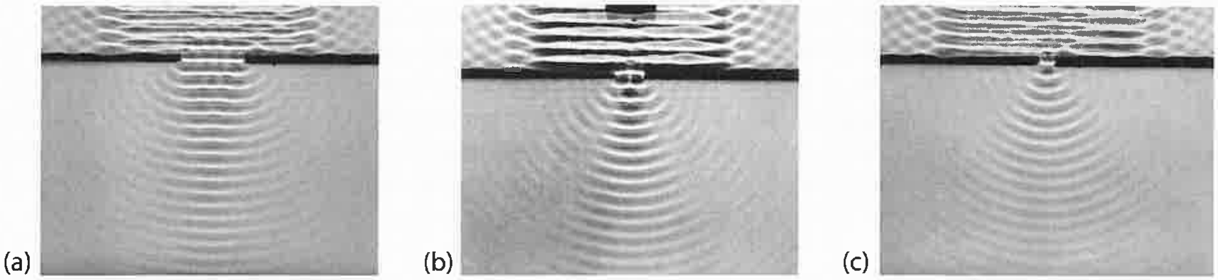


FIGURE 29.7

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.

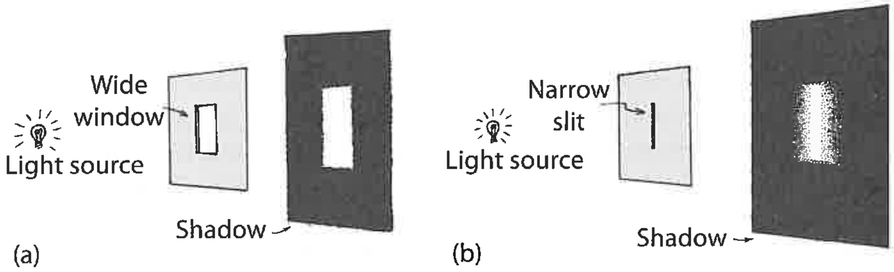
When light passes through an opening that is large compared with the wavelength of light, it casts a shadow such as the one shown in Figure 29.8a. We see a rather sharp boundary between the light and dark area of the shadow. But if we pass light through a thin razor slit in a piece of opaque cardboard, we see that the light diffracts (Figure 29.8b). The sharp boundary between the light and dark area 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.

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

(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.



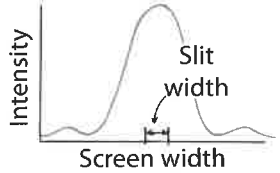


FIGURE 29.9

Graphic interpretation of diffracted light through a single thin slit.

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 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 to 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 29.10

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.

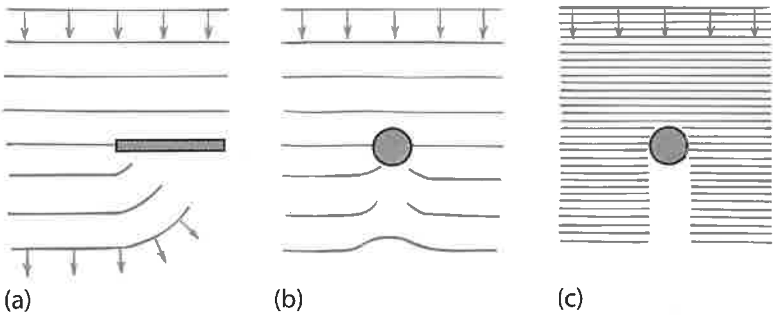
Diffraction is not confined to narrow slits or to openings in general but can be seen for all shadows. On close examination, even the sharpest shadow is blurred slightly at the edge. When the light is of a single color (monochromatic), diffraction can produce *diffraction fringes* at the edge of the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

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 that 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.

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 defeat this fundamental diffraction limit.

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.



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.

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, and 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).

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

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.

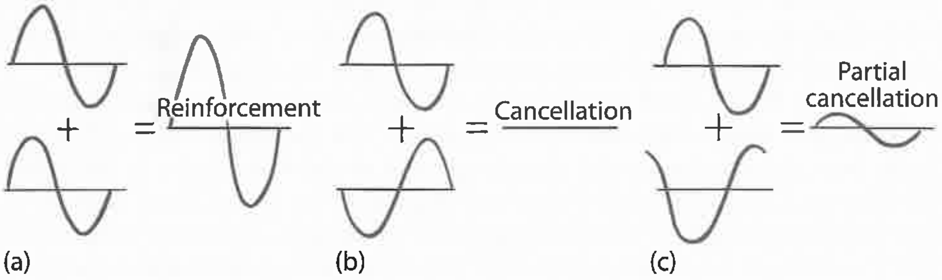


FIGURE 29.12
Wave interference.

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.

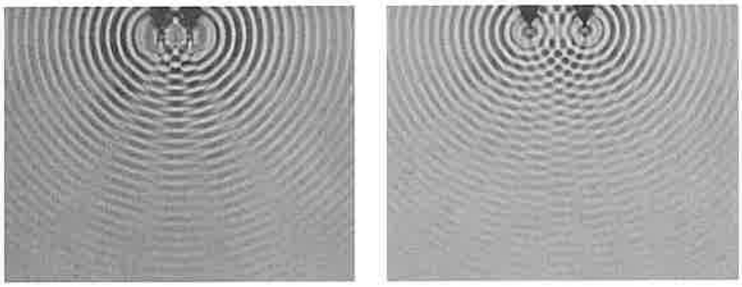
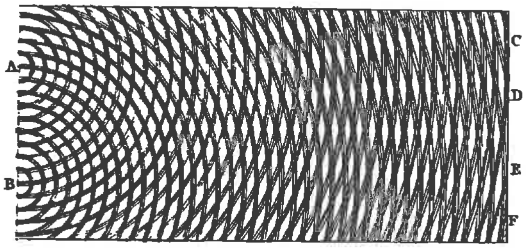


FIGURE 29.14
Interference patterns of overlapping waves from two vibrating sources.

Under more carefully controlled conditions, interesting patterns are produced by a pair of wave sources placed side by side (Figure 29.14). Drops of water are allowed to fall at a controlled frequency into shallow tanks of water (ripple tanks similar to Jennie's in the chapter opener) while their patterns 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 29.15
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. Letters C, D, E, and F mark regions of destructive interference.

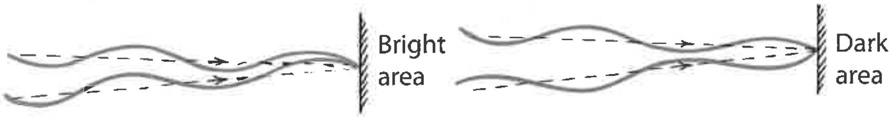


In 1801, the wave nature of light was convincingly demonstrated when the British physicist and physician Thomas Young performed his now famous interference experiment.[1] Young found that light directed through two closely spaced pinholes recombines to produce fringes of brightness and darkness on a 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 done with two closely spaced slits instead of pinholes, the fringe patterns are straight lines (Figure 29.17).

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 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 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 only through the slit just

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.



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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 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!

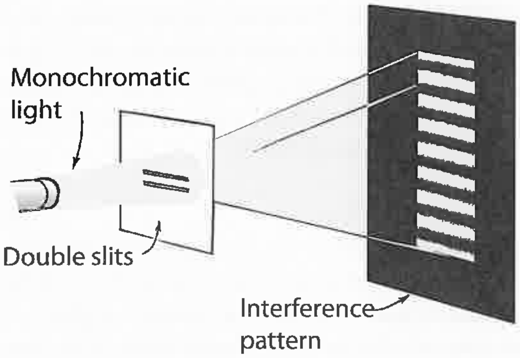


FIGURE 29.17

INTERACTIVE FIGURE

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

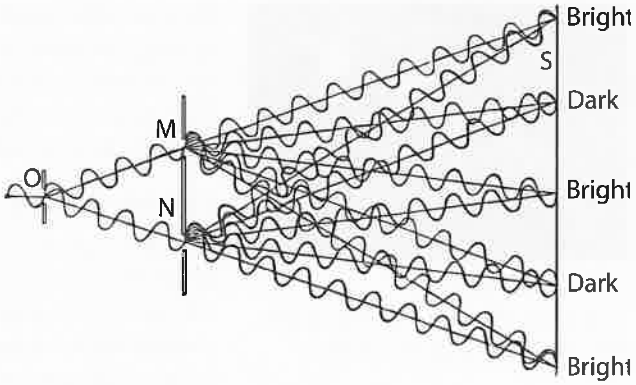


FIGURE 29.18

INTERACTIVE FIGURE

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

uncovered, we get the same illumination on the screen, only 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.

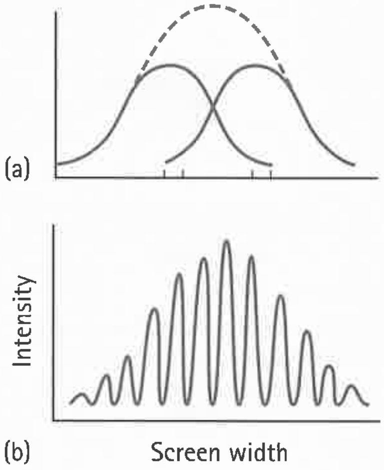


FIGURE 29.19

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.

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

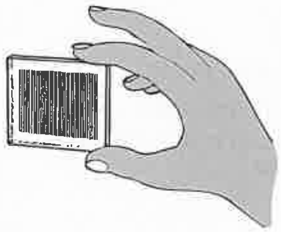
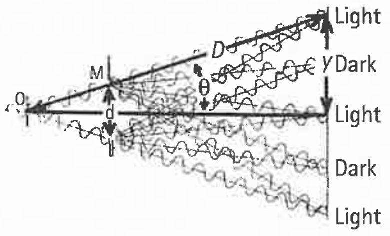


FIGURE 29.20

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



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[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. D is the distance from the fringe to the slits (which, in practice, is much greater than shown here).

devices called *spectrometers,* which we will discuss in the next chapter. 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 by diffraction are especially vivid on the reflective surfaces of DVDs.

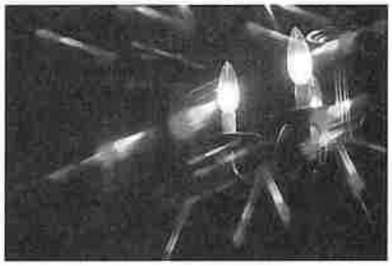

FIGURE 29.21

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

SINGLE-COLOR THIN-FILM INTERFERENCE

Another way interference fringes can be produced is by the reflection of light from the top and bottom surfaces of a thin film. A simple demonstration can be set up with a monochromatic light source and a couple of pieces of glass. A sodium-vapor lamp provides 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.

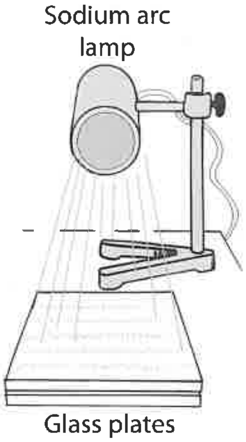

FIGURE 29.22

Interference fringes produced when monochromatic light is reflected from two plates of glass with an air wedge between them.

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]

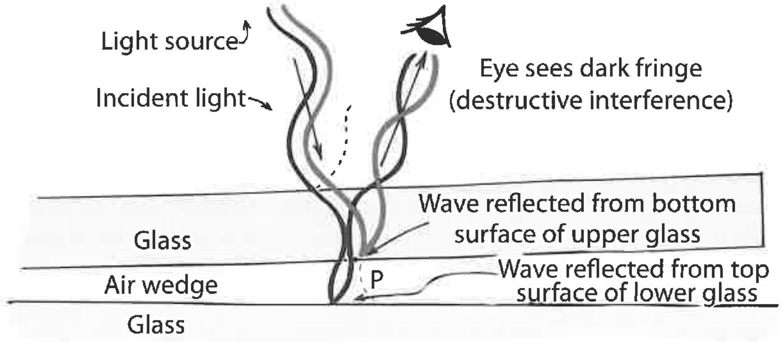

FIGURE 29.23

Reflection from the upper and lower surfaces of a "thin film of air."

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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 less (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 180° 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.

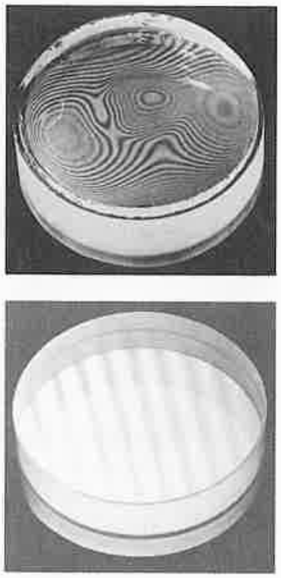

FIGURE 29.24

Optical flats used for testing the flatness of surfaces.

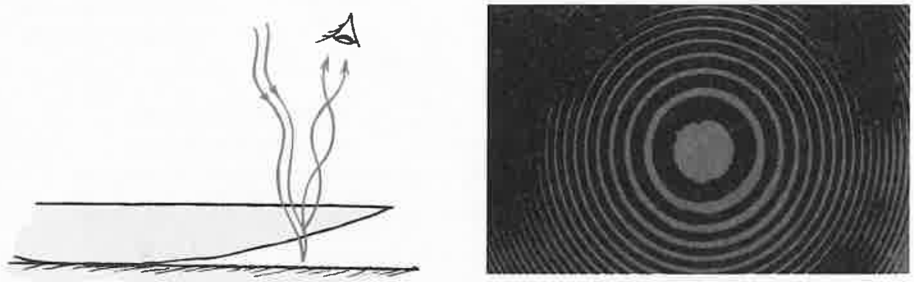

FIGURE 29.25

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 longer-wavelength red light than for the shorter waves of blue light. Do you see the geometrical reason for this?

INTERFERENCE COLORS BY REFLECTION FROM THIN FILMS

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, yellow light. When yellow light is subtracted from white light, the mixture left will appear as the complementary color of yellow, which is blue. 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.

PhysicsPlace.com™
Video
Soap Bubble Interference

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.

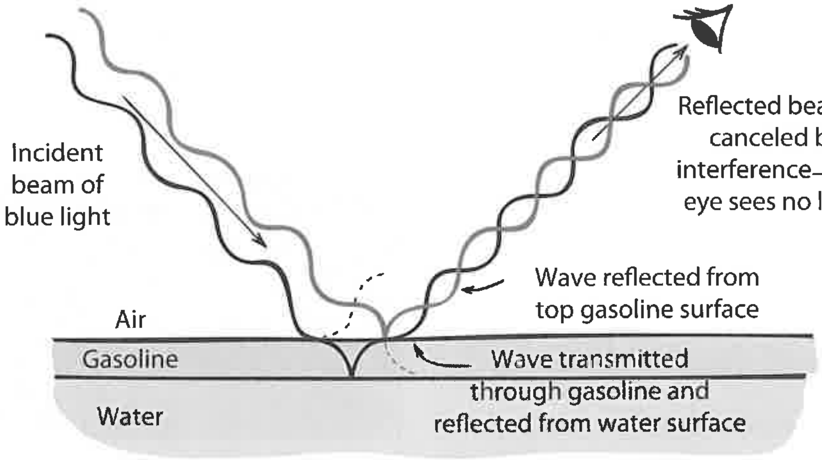

FIGURE 29.26
The thin film of gasoline is just the right thickness to cancel the reflections of blue light from the top and bottom surfaces. If the film were thinner, perhaps shorter-wavelength violet would be canceled. (One wave is drawn in black to show how it is out of phase with the blue wave upon 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.

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

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.

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. The top becomes thinner, so thin that it appears black. This tells you that its thickness is less than one-fourth the wavelength of the shortest waves of visible light. 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.

CHECK POINT

In the left column are the colors of certain objects. In the right column are various ways in which colors are produced. Match the right column to the left.

1. yellow daffodil	**a.** interference
2. blue sky	**b.** selective reflection
3. rainbow	**c.** refraction
4. soap bubble	**d.** scattering

Check Your Answers

1. b; **2.** d; **3.** c; **4.** a

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 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. Polarization can be understood when we shake a taut rope as 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 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.

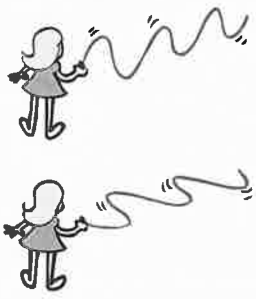

FIGURE 29.28

A vertically plane-polarized wave and 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. 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).

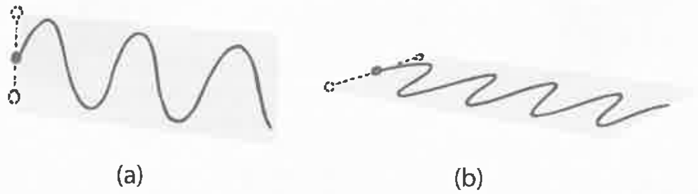
(a) (b)

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.

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Video
Polarized Light and 3-D Viewing

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 emitting the light. The planes of vibration might be as numerous as the accelerating electrons producing 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.

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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.

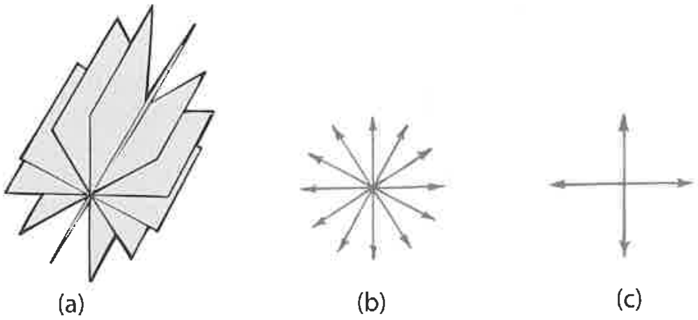

FIGURE 29.30
Representations of plane-polarized waves. The three representations show the electric part of the electromagnetic wave.

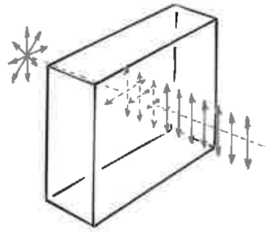

FIGURE 29.31
One component of the incident unpolarized light is absorbed, resulting in emerging polarized light.

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 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 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. (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]

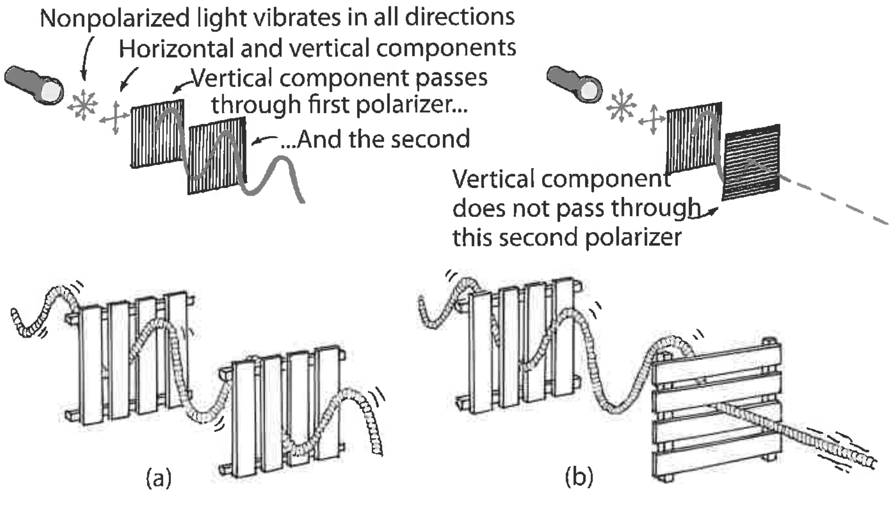

FIGURE 29.32
A rope analogy illustrates the effect of crossed Polaroids.

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[5] Called *dichroic*.

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

[7] In a common Polaroid filter, long-chain molecules are oriented with their axis perpendicular to the polarizing axis, and 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.

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 29.34). 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.

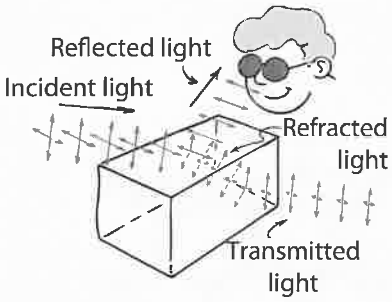


FIGURE 29.34
Most glare from nonmetallic surfaces is polarized. Note how components of incident light parallel to the surface are reflected and how components perpendicular to the surface pass through the surface into the medium.

FIGURE 29.33
Polaroid sunglasses block out horizontally vibrating light. When the lenses overlap at right angles, no light gets through.

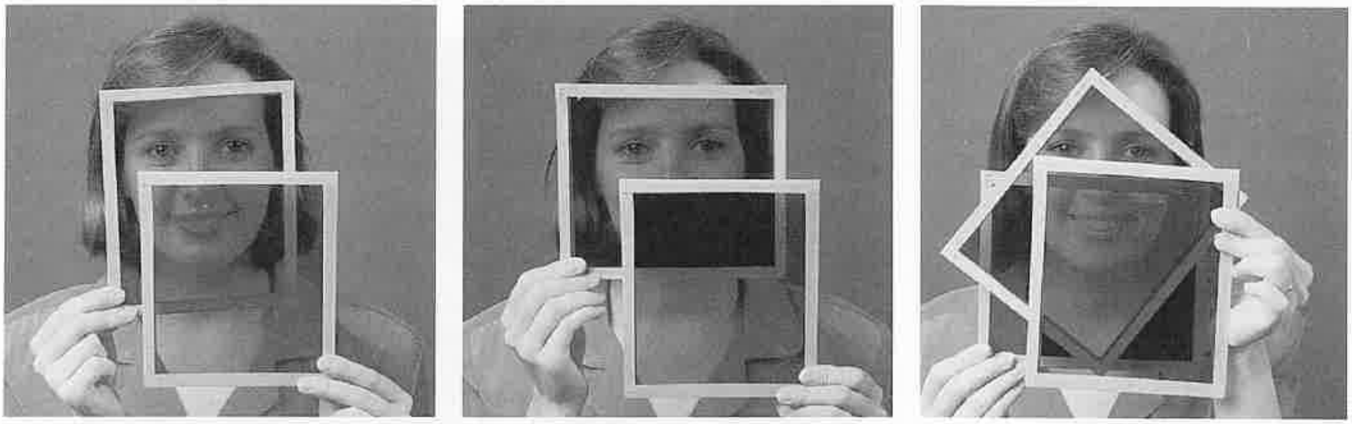


FIGURE 29.35
Light is transmitted when the axes of the Polaroids are aligned (a), but absorbed when Ludmila rotates one so that the axes are at right angles to each other (b). When she inserts a third Polaroid at an angle between the crossed Polaroids, light is again transmitted (c). Why? (For the answer—after you have given this some thought—see Appendix D, "More About Vectors.")

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

CHECK POINT

Which pair of glasses 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.

THREE-DIMENSIONAL VIEWING

Vision in three dimensions depends primarily on the fact that both eyes give their impressions simultaneously (or nearly so), each eye viewing the scene from a slightly different angle. To convince yourself that each eye sees a different view, hold 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. The drawings of Figure 29.36 illustrate a stereo view of the crystal structure of ice.

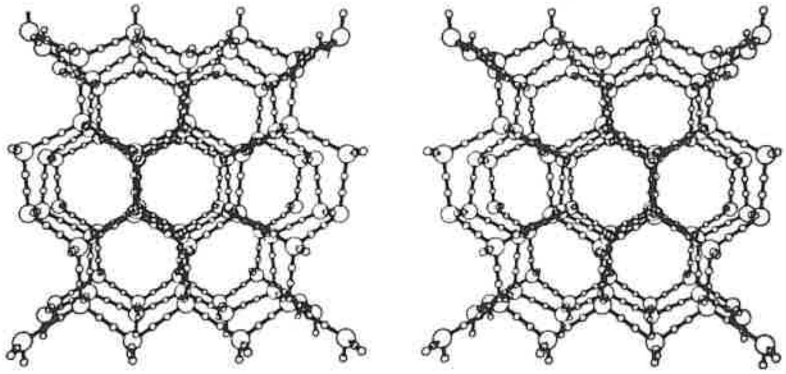


FIGURE 29.36

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!)

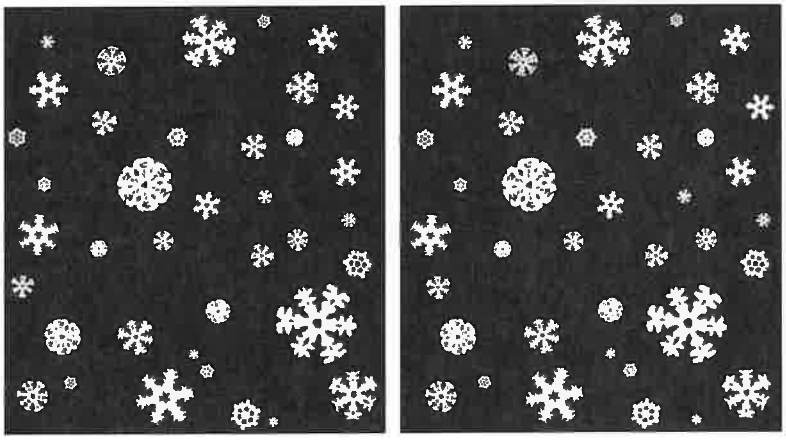


FIGURE 29.37

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

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.

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 29.38). You then will see an image in three dimensions.

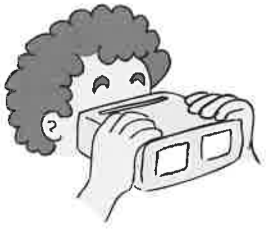


FIGURE 29.38
A stereoscopic viewer.

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.
Experiment is the *sole judge*
of scientific "truth."
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.

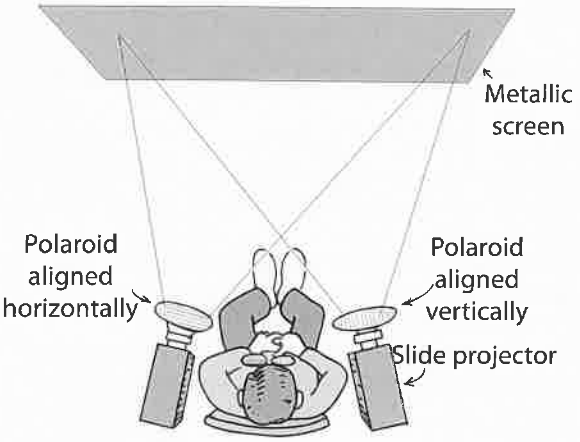


FIGURE 29.40
A 3-D show using Polaroids. The left eye sees only polarized light from the left projector, the right eye sees only polarized light from the right projector, and both views merge in the brain to produce depth.

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 previous stereo figures. Once you've mastered the viewing technique, head for the local mall and check the variety of stereograms in posters and books.

fyi

- Cosmic microwave background (CMB) fills all of space and comes at us from every direction. It is an echo of the Big Bang that got our universe started nearly 14 billion years ago. Recent findings show this radiation to be ever so slightly polarized and with slight variations of polarization from one direction to another. Polarization observations help to provide a clear and detailed look at the early cosmos.

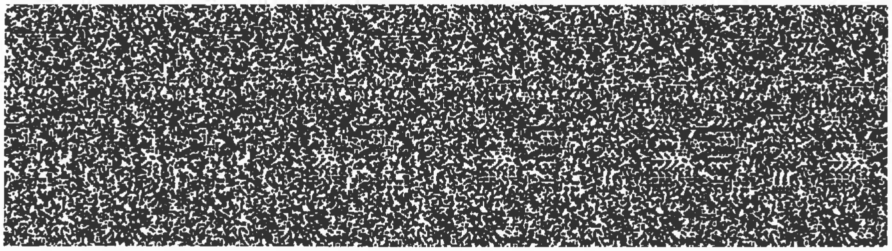


FIGURE 29.41
A computer-generated stereogram.

Holography

Perhaps the most exciting illustration of interference is the **hologram,** a two-dimensional photographic plate illuminated 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. *Holo* in Greek means "whole," and *gram* in Greek means "message" or "information." 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

fyi

- 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.

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 the next chapter.) 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 web.

SUMMARY OF TERMS

Huygens' principle Every point on a wavefront can be regarded as a new source of wavelets, which combine to produce the next wavefront, whose points are sources of further wavelets, and so on.

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.

REVIEW QUESTIONS

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 as plane waves?

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 is more easily diffracted around buildings, AM or FM radio waves? Why?

Superposition and Interference

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

Single-Color Thin-Film Interference

8. What accounts for the light and dark bands produced when monochromatic light reflects from a glass pane atop another glass pane?
9. What is meant by saying a surface is *optically flat?*
10. What is the cause of Newton's rings?

Interference Colors by Reflection from Thin Films

11. What produces iridescence?
12. What causes the spectrum of colors seen in gasoline splotches on a wet street? Why are these not 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?

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?

Three-Dimensional Viewing

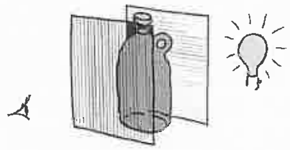
20. Why would depth not be perceived if you viewed duplicates of ordinary slides in a stereo viewer (Figure 29.39), rather than the pairs of slides taken with a stereo camera?
21. What role do polarization filters play in a 3-D movie?

Holography

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

PROJECTS

1. 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 it with two closely spaced slits.
2. 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—for what you see depends on your point of view!
3. 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.
4. 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.



EXERCISES

1. Why can sunlight that illuminates Earth be approximated by plane waves, whereas the light from a nearby lamp cannot?
2. In our everyday environment, diffraction is much more evident for sound waves than for light waves. Why is this so?
3. Why do *radio waves* diffract around buildings, while *light waves* do not?
4. How are interference fringes of light analogous to the varying intensity that you hear as you walk past a pair of speakers emitting the same sound?
5. By how much should a pair of light rays from a common source differ in distance traveled to produce destructive interference?
6. 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?
7. A double-slit arrangement produces interference fringes for yellow sodium light. To produce narrower-spaced fringes, should red light or blue light be used?
8. 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?
9. Which will give wider-spaced fringes in a double-slit experiment, red light or violet light? (Let Figure 29.18 guide your thinking.)
10. Which will give wider-spaced fringes, a double-slit experiment in air or in water? (Let Figure 29.18 guide your thinking.)
11. 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?
12. 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?
13. 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?
14. 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?
15. 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?
16. What happens to the distance between interference fringes if the separation between two slits is increased?
17. Why is Young's experiment more effective with slits than with the pinholes he first used?
18. In which of these is color formed by refraction—flower petals, rainbow, soap bubbles? By selective reflection? By thin-film interference?
19. 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?
20. 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?
21. Why do the iridescent colors seen in some seashells (such as abalone shells) change as the shells are viewed from various positions?
22. When dishes are not properly rinsed after washing, different colors are reflected from their surfaces. Explain.
23. Why are interference colors more apparent for thin films than for thick films?
24. Will the light from two very close stars produce an interference pattern? Explain.
25. 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?

26. 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)?

27. For the Hubble Space Telescope, which light—red, green, blue, or ultraviolet—is better for seeing fine detail of distant astronomical objects?

28. Polarized light is a part of nature, but polarized sound is not. Why?

29. The digital displays of watches and other devices are normally polarized. What related problem can occur when wearing Polaroid sunglasses?

30. Why will an ideal Polaroid filter transmit 50% of incident nonpolarized light?

31. Why may an ideal Polaroid filter transmit anything from zero to 100% of incident polarized light?

32. 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?

33. How can you determine the polarization axis for a single sheet of Polaroid (especially if you're at the edge of a lake)?

34. Why do Polaroid sunglasses reduce glare, whereas nonpolarized sunglasses simply cut down the total amount of light reaching the eyes?

35. To remove the glare of light from a polished floor, should the axis of a Polaroid filter be horizontal or vertical?

36. Most of the glare from nonmetallic surfaces is polarized, the axis of polarization being parallel to that of the reflecting surface. Would you expect the polarization axis of Polaroid sunglasses to be horizontal or vertical? Why?

37. 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.)

38. 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), some light does get through. Why?

39. Why did practical holography have to await the advent of the laser?

40. Which of these is most central to holography—interference, selective reflection, refraction, or all of these?

CHAPTER 29 ONLINE RESOURCES

PhysicsPlace.com™

Interactive Figures

- 29.3, 29.4, 29.8, 29.17, 29.18

Videos

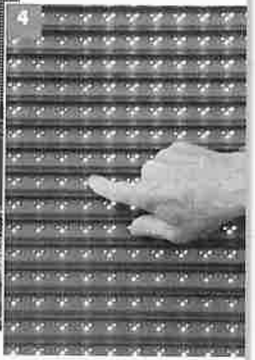
- Soap Bubble Interference
- Polarized Light and 3-D Viewing

Quizzes

Flashcards

Links

30 Light Emission



1 George Curtis separates light from an argon source into its component frequencies with a spectroscope. 2 The aurora borealis (northern lights) and aurora australis (southern lights) are produced by charged particles thrown off from the Sun, which make impact with and excite atoms and molecules high in the sky. 3 Evan Jones points to an extensive use of light-emitting diodes (LEDs) in a billboard near his college. 4 The LEDs are arranged in sets of the three additive primaries: red, green, and blue. All colors of the rainbow are activated by turning on various combinations of LEDs.

Walter Steiger is a stargazer. His interest in stars centers on the light they emit and how they do so. I met Walter when I first visited the University of Hawaii at Manoa in the mid-1970s. At that time, he was chairman of the physics department. I was impressed to meet the pioneer of astronomy in Hawaii, for he was the first scientist to install an interim solar observatory at nearby Makapuu Point, and later a permanent facility atop Haleakala in Maui. His pioneering work led to the development of the first telescope atop Mauna Kea on the Big Island, which is now home to some of the leading telescopes on planet Earth.

After retirement from the Manoa campus, Walter served as the manager of the Science Center of the B. P. Bishop Museum in Honolulu until 1986. He then moved to Hilo and served 5 years as the site manager of the Caltech Submillimeter Observatory on Mauna Kea. Since 1993, he has lectured on physics and astronomy at the University of Hawaii at Hilo. I also lectured in physics there and we have been close friends since. Walter's many interests include photography, in which he has won various awards. For a time, he and I enjoyed making pottery together—justifiably winning *no* prizes.

Humans know about as much about the atmospheres of stars as they do about the atmosphere of Earth. That's because the light emitted by stars, and everything else, tells us what atoms make up the emitters. This chapter examines the emission of light, which is fascinating to astronomers, physicists, and, I hope, you too.

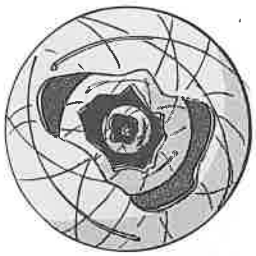


FIGURE 30.1
Simplified view of electrons orbiting in discrete shells about the nucleus of an atom.

Light Emission

If energy is pumped into a metal antenna in such a way that it causes free electrons to vibrate to and fro a few hundred thousand times per second, a radio wave is emitted. If the free electrons could be made to vibrate to and fro on the order of a million billion times per second, a visible light wave would be emitted. But light is not produced from metallic antennae, nor is it exclusively produced by atomic antennae via oscillations of electrons in atoms, as discussed in previous chapters. In this chapter, we discuss the physics of light sources—of light *emission.*

The details of light emission from atoms involve the transitions of electrons from higher to lower energy states within the atom. This emission process can be understood in terms of the familiar planetary model of the atom that we discussed in Chapter 11. Just as each element is characterized by the number of electrons that occupy the shells surrounding its atomic nucleus, each element also possesses its own characteristic pattern of electron shells, or energy states. These states are found only at certain energies; we say they are *discrete.* We call these discrete states *quantum states,* and we'll return to them in detail in the next two chapters. For now, we'll concern ourselves only with their role in light emission.

Excitation

An electron farther from the nucleus has a greater electric potential energy with respect to the nucleus than an electron nearer the nucleus. We say that the more distant electron is in a higher energy state, or, equivalently, at a higher energy level. In a sense, this is similar to the energy of a spring door or a pile driver. The wider the door is pulled open, the greater its spring potential energy; the higher the ram of a pile driver is raised, the greater its gravitational potential energy.

Everything in nature is connected. Even islands are connected underneath.

When an electron is in any way raised to a higher energy level, the atom is said to be *excited.* The electron's higher position is only momentary: Like the pushed-open spring door, it soon returns to its lowest energy state. The atom loses its temporarily acquired energy when the electron returns to a lower level and emits radiant energy. The atom has undergone the process of **excitation** and *de-excitation.*

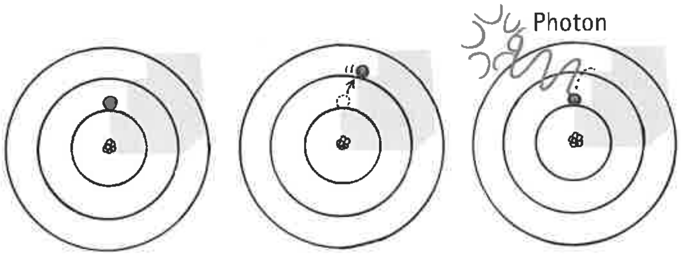


FIGURE 30.2
INTERACTIVE FIGURE
When an electron in an atom is boosted to a higher orbit, the atom is excited. When the electron returns to its original orbit, the atom de-excites and emits a photon of light.

Just as each electrically neutral element has its own number of electrons, each element also has its own characteristic set of energy levels. Electrons dropping from higher to lower energy levels in an excited atom emit with each jump a throbbing pulse of electromagnetic radiation called a *photon,* the frequency of which is related to the energy transition of the jump. We think of this photon as a localized corpuscle of pure energy—a "particle" of light—which is ejected from the atom. The frequency of the photon is directly proportional to its energy. In shorthand notation,

$$E \sim f$$

When the proportionality constant h is introduced, this becomes the exact equation

$$E = hf$$

where h is Planck's constant (more about this in the next chapter). A photon in a beam of red light, for example, carries an amount of energy that corresponds to its frequency. Another photon of twice the frequency has twice as much energy and is found in the ultraviolet part of the spectrum. If many atoms in a material are excited, many photons with many frequencies are emitted that correspond to the many different levels excited. These frequencies correspond to characteristic colors of light from each chemical element.

The light emitted in the glass tubes of advertising signs is a familiar consequence of excitation. The different colors in the signs correspond to the excitation of different gases, although it is common to refer to any of these as "neon." Only the red light is that of neon. At the ends of the glass tube that contains the neon gas are electrodes. Electrons are boiled off these electrodes and are jostled back and forth at high speeds by a high ac voltage. Millions of high-speed electrons vibrate back and forth inside the glass tube and smash into millions of target atoms, boosting orbital electrons into higher energy levels by an amount of energy equal to the decrease in kinetic energy of the bombarding electron. This energy is then radiated as the characteristic red light of neon when the electrons fall back to their stable orbits (to their ground states). The process occurs and recurs many times, as neon atoms continually undergo a cycle of excitation and de-excitation. The overall result of this process is the transformation of electrical energy into radiant energy.

The colors of various flames are due to excitation. Different atoms in the flame emit colors characteristic of their energy-level spacings. Common table salt placed in a flame, for example, produces the characteristic yellow of sodium. Every element, excited in a flame or otherwise, emits its own characteristic color or colors.

Street lamps provide another example. City streets are illuminated with light emitted by gases such as mercury vapor. The light from these lamps is rich in blues and violets and therefore is a different "white" than the light from previous incandescent lamps. Most street lamps use the glow of sodium gas, which consumes less energy. Sodium vapor lamps have an orange-yellow tint. See if your instructor has a spare prism or diffraction grating you can borrow. Look through the prism or grating at the light from street lamps and see the discreteness of the colors, which indicates the discreteness of the atomic levels. Note the different colors of mercury and sodium lamps.

Excitation is illustrated in the aurora borealis and australis (as pictured in the chapter opener). High-speed charged particles that originate in the solar wind strike atoms and molecules in the upper atmosphere. They emit light exactly as occurs in a neon tube. The different colors in the aurora correspond to the excitation of different gases—oxygen atoms produce a greenish-white color, nitrogen molecules produce red-violet, and nitrogen ions produce a blue-violet color. Auroral emissions are not restricted to visible light; they also include infrared, ultraviolet, and X-ray radiation.

The excitation/de-excitation process can be accurately described only by quantum mechanics. An attempt to view the process in terms of classical physics runs into contradictions. Classically, an accelerating electric charge produces electromagnetic radiation. Does this explain light emission by excited atoms? An electron does accelerate in a transition from a higher to a lower energy level. Just as the innermost planets of the solar system have greater orbital speeds than those in the outermost orbits, the electrons in the innermost orbits of the atom have greater speeds. An electron gains speed in dropping to lower energy levels. Fine—the accelerating electron radiates a photon! But not so fine—the electron is continually undergoing acceleration (centripetal acceleration) in any orbit, whether or not it changes energy levels. According to classical physics, it should continually radiate energy. But it doesn't. All attempts to explain the emission of light by an excited atom in terms of a classical

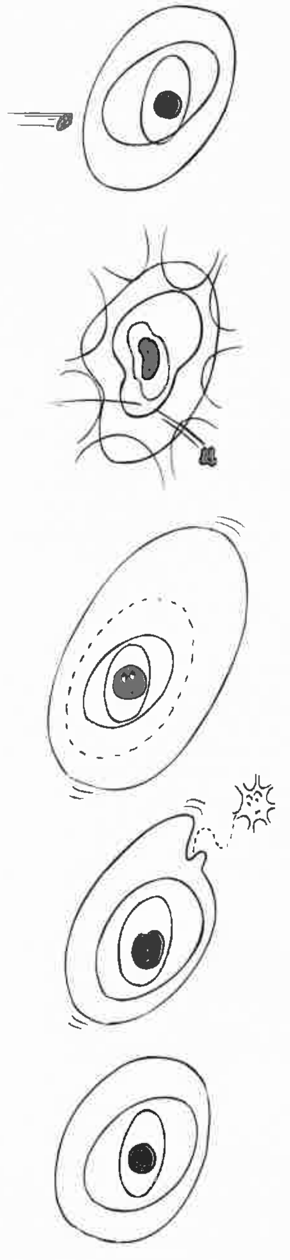


FIGURE 30.3
Excitation and de-excitation.

Exciting an atom is like trying to kick a ball out of a ditch. Many short kicks won't do the job, because the ball keeps falling back. A kick of just the right amount of energy is enough to get the ball out of the ditch. Likewise with the excitation of atoms.

model have been unsuccessful. We shall simply say that light is emitted when an electron in an atom makes a "quantum jump" from a higher to a lower energy level and that the energy and frequency of the emitted photon are described by $E = hf$.

CHECK POINT

Suppose a friend suggests that, for a first-rate operation, the gaseous neon atoms in a neon tube should be periodically replaced with fresh atoms because the energy of the atoms tends to be used up with continued excitation, producing dimmer and dimmer light. What do you say to this?

Check Your Answer

The neon atoms don't release any energy that is not given to them by the electric current in the tube and therefore don't get "used up." Any single atom may be excited and re-excited without limit. If the light is, in fact, becoming dimmer and dimmer, it is probably because a leak exists. Otherwise, there is no advantage whatsoever to changing the gas in the tube, because a "fresh" atom is indistinguishable from a "used" one. Both are ageless and older than the solar system.

Emission Spectra

Every element has its own characteristic pattern of electron energy levels and therefore emits light with its own characteristic pattern of frequencies, its **emission spectrum,** when excited. This pattern can be seen when light is passed through a prism—or, better, when it is first passed through a thin slit and then focused through a prism onto a viewing screen behind. Such an arrangement of slit, focusing lenses, and prism (or diffraction grating) is called a **spectroscope,** one of the most useful instruments of modern science (Figure 30.4).

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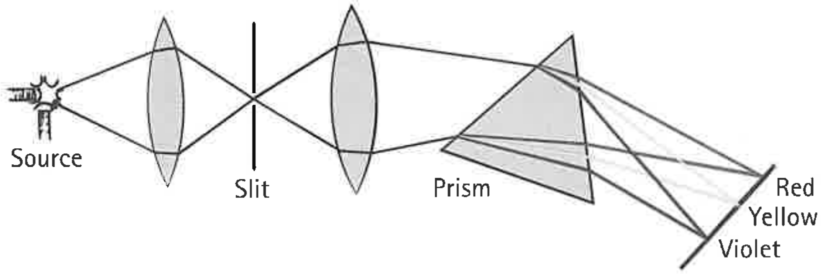

FIGURE 30.4

A simple spectroscope. Images of the illuminated slit are cast on a screen and make up a pattern of lines. The spectral pattern is characteristic of the light used to illuminate the slit.

Each component color is focused at a definite position, according to its frequency, and forms an image of the slit on the screen, photographic film, or appropriate detector. The different-colored images of the slit are called *spectral lines.* Some typical spectral patterns labeled by wavelengths are shown in Figure 30.5. It is customary to refer to colors in terms of their wavelengths rather than their frequencies. A given frequency corresponds to a definite wavelength.[1]

If the light given off by a sodium-vapor lamp is analyzed in a spectroscope, a single yellow line predominates—a single image of the slit. If we narrow the width of the slit, we find that this line is really composed of two very close lines. These lines correspond

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[1] Recall, from Chapter 19, that $v = f\lambda$, where v is the wave speed, f is the wave frequency, and λ (lambda) is the wavelength. For light, v is the constant c, so we see from $c = f\lambda$ the relationship between frequency and wavelength—namely, $f = \frac{c}{\lambda}$ and $\lambda = \frac{c}{f}$.


(a) incandescent bulb


(b) hydrogen


(c) sodium


(d) mercury

FIGURE 30.5

INTERACTIVE FIGURE

(a) An incandescent bulb has a continuous spectrum. Each of the three elements (b) hydrogen, (c) sodium, and (d) mercury has a different line spectrum.

to the two predominant frequencies of light emitted by excited sodium atoms. The rest of the spectrum looks dark. (Actually, there are many other lines, often too dim to be seen with the naked eye.) The same happens with all glowing vapors. The light from a mercury-vapor lamp shows a pair of bright yellow lines close together (but in different positions from those of sodium), a very intense green line, and several blue and violet lines. A neon tube produces a more complicated pattern of lines. We find that the light emitted by each element in the vapor phase produces its own characteristic pattern of lines. These lines correspond to the electron transitions between atomic energy levels and are as characteristic of each element as are the fingerprints of people. The spectroscope, therefore, is widely used in chemical analysis.

The next time you see evidence of atomic excitation, perhaps the green flame produced when a piece of copper is placed in a fire, squint your eyes and see if you can imagine electrons jumping from one energy level to another in a pattern characteristic of the atom being excited—a pattern that displays a color unique to that atom. That's what's happening!

fyi

- Because every chemical element has its own *unique* set of energy levels, each element also has its own *distinctive pattern* of spectral absorption (and emission) lines—the *spectral "fingerprint"* that astronomers use to identify various chemical elements in astronomical objects.

CHECK POINT

Spectral patterns are not shapeless smears of light but, instead, consist of fine and distinct straight lines. Why is this so?

Check Your Answer

The spectral lines are simply images of the slit, which is itself a thin, straight opening through which light is admitted before being spread by the prism (or diffraction grating). When the slit is adjusted to make its most narrow opening, closely spaced lines can be resolved (distinguished from one another). A wider slit admits more light, which permits easier detection of dimmer radiant energy. But width is at the expense of resolution when closely spaced lines blur together.

Incandescence

Light that is produced as a result of high temperature has the property of **incandescence** (from a Latin word meaning "to grow hot"). It can have a reddish tint, as from the heating element of a toaster, or a bluish tint, as from a particularly hot star. Or it can be white, as from the familiar incandescent lamp. What sets incandescent light apart from the light of a neon tube or mercury vapor lamp is that it contains an infinite number of frequencies, spread smoothly across the spectrum. Does this mean that an infinite number of energy levels characterizes the tungsten atoms making up the filament of the incandescent lamp? The answer is no; if the filament were vaporized and then excited, the tungsten gas would emit light with a finite number of frequencies and produce an overall bluish color. Light emitted by atoms far from one another in the gaseous phase is quite different from the light emitted by the same atoms closely packed in the solid phase. This is analogous to the differences in sound from an isolated ringing bell and from a box crammed with ringing bells (Figure 30.6). In a gas, the atoms are far apart. Electrons undergo transitions between energy levels within the atom quite unaffected by the presence of neighboring atoms. But when the atoms are closely packed, as in a solid, electrons of the outer orbits make transitions not only within the energy levels of their "parent" atoms but also between the levels of neighboring atoms. They bounce around over dimensions larger than a single atom, resulting in an infinite variety of transitions—hence the infinite number of radiant-energy frequencies.

FIGURE 30.6

The sound of an isolated bell rings with a clear and distinct frequency, whereas the sound emanating from a box of bells crowded together is discordant. Likewise with the difference between the light emitted from atoms in the gaseous state and that from atoms in the solid state.

As might be expected, incandescent light depends on temperature, because it is a form of thermal radiation. A plot of radiated energy over a wide range of frequencies for two different temperatures is shown in Figure 30.7. (Recall that we treated the radiation curve for sunlight back in Chapter 27 and discussed blackbody radiation in Chapter 16.) As the solid is heated further, more high-energy transitions occur, and higher-frequency radiation is emitted. The curve comprises a continuous spectrum. In the brightest part of the spectrum, the predominant frequency of emitted radiation, the *peak frequency*, is directly proportional to the absolute temperature of the emitter:

$$\bar{f} \sim T$$

We use the bar above the f to indicate the peak frequency, for radiations of many frequencies are emitted from the incandescent source. If the temperature of an object (in kelvins) is doubled, the peak frequency of emitted radiation is doubled. The electromagnetic waves of violet light have nearly twice the frequency of red light waves. A violet-hot star, therefore, has nearly twice the surface temperature of a red-hot star.[2] The temperature of incandescent bodies, whether they be stars or blast-furnace interiors, can be determined by measuring the peak frequency (or color) of the radiant energy they emit.

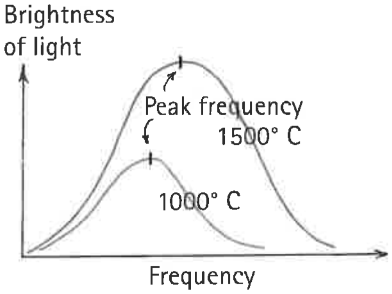

FIGURE 30.7

INTERACTIVE FIGURE

Radiation curves for an incandescent solid.

CHECK POINT

From the radiation curves shown in Figure 30.7, which emits the higher average frequency of radiant energy—the 1000°C source or the 1500°C source? Which emits more radiant energy?

Check Your Answers

The 1500°C radiating source emits the higher average frequencies, as noted by the extension of the curve to the right. The 1500°C source is brighter and also emits more radiant energy, as noted by its greater vertical displacement.

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[2] If you study this topic further, then as mentioned in footnote 3 of Chapter 16, you will find that the time rate at which an object radiates energy (the radiated power) is proportional to the fourth power of its Kelvin temperature. So a doubling of temperature corresponds to a doubling of the frequency of radiant energy but a sixteenfold increase in the rate of emission of radiant energy.

Absorption Spectra

When we view white light from an incandescent source with a spectroscope, we see a continuous spectrum over the whole rainbow of colors. If a gas is placed between the source and the spectroscope, however, careful inspection will show that the spectrum is not quite continuous. This is an **absorption spectrum,** and there are dark lines distributed throughout it; these dark lines against a rainbow-colored background are like emission lines in reverse. These are *absorption lines.*

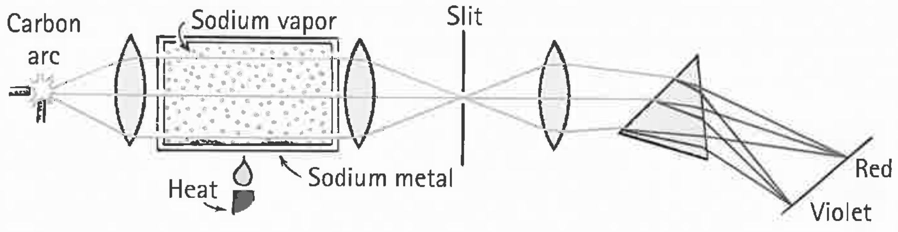

FIGURE 30.8

INTERACTIVE FIGURE

Experimental arrangement for demonstrating the absorption spectrum of a gas.

Atoms absorb light as well as emit light. An atom will most strongly absorb light having the frequencies to which it is tuned—some of the same frequencies it emits. When a beam of white light passes through a gas, the atoms of the gas absorb light of selected frequencies from the beam. This absorbed light is reradiated, but in *all* directions instead of only in the direction of the incident beam. When the light remaining in the beam spreads out into a spectrum, the frequencies that were absorbed appear as dark lines in the otherwise continuous spectrum. The positions of these dark lines correspond exactly to the positions of lines in an emission spectrum of the same gas (Figure 30.9).

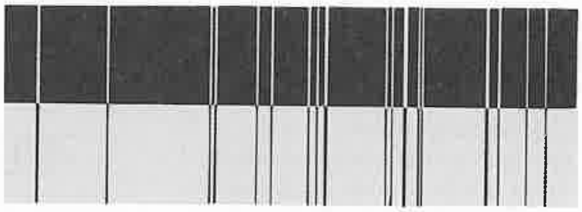

FIGURE 30.9

Emission and absorption spectra.

Although the Sun is a source of incandescent light, the spectrum it produces, upon close examination, is not continuous. There are many absorption lines, called *Fraunhofer lines* in honor of the Bavarian optician and physicist Joseph von Fraunhofer, who first observed and mapped them accurately. Similar lines are found in the spectra produced by the stars. These lines indicate that the Sun and stars are each surrounded by an atmosphere of cooler gases that absorb some of the frequencies of light coming from the main body. Analysis of these lines reveals the chemical composition of the atmospheres of such sources. We find from these analyses that the stellar elements are the same elements that exist on Earth. An interesting sidelight is that, in 1868, spectroscopic analysis of sunlight showed some spectral lines different from any known on Earth. These lines identified a new element, which was named *helium,* after Helios, the Greek god of the Sun. Helium was discovered in the Sun before it was discovered on Earth. How about that!

We can determine the speed of stars by studying the spectra they emit. Just as a moving sound source produces a Doppler shift in its pitch (Chapter 19), a moving light source produces a Doppler shift in its light frequency. The frequency (not the speed!) of light emitted by an approaching source is higher, while the frequency of light from a receding source is lower, than the frequency of light from a stationary source. The corresponding spectral lines are displaced toward the red end of the spectrum for receding sources. Since the universe is expanding, almost all the galaxies show a red shift in their spectra.

We shall see, in Chapter 31, how the spectra of elements enable us to determine atomic structure.

The Andromeda galaxy is approaching us, emitting light toward Earth that is blue-shifted.

CHECK POINT

Distinguish between *emission spectra, continuous spectra,* and *absorption spectra.*

Check Your Answer

Emission spectra are produced by thin gases in which the atoms do not experience many collisions. Continuous spectra result when atoms continually collide, which is why solids, liquids, or dense gases emit light at all the visible frequencies when heated. Absorption spectra occur when light passes through a dilute gas and atoms in the gas absorb at characteristic frequencies. Because the re-emitted light is unlikely to be emitted in the same direction as the absorbed photons, dark lines (absence of light) occur in the spectrum.

Fluorescence

Thermal agitation and bombardment by particles, such as high-speed electrons, are not the only means of imparting excitation energy to an atom. An atom may be excited by absorbing a photon of light. From the relationship $E = hf$, we see that high-frequency light, such as ultraviolet, which lies beyond the visible spectrum, delivers more energy per photon than lower-frequency light. Many substances undergo excitation when illuminated with ultraviolet light.

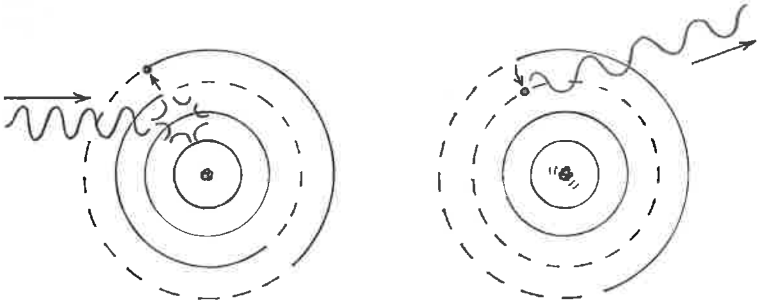

FIGURE 30.10

INTERACTIVE FIGURE

In fluorescence, the energy of the absorbed ultraviolet photon boosts the electron in an atom to a higher energy state. When the electron then returns to an intermediate state, the photon emitted is less energetic and therefore of a lower frequency than the ultraviolet photon.

Many materials that are excited by ultraviolet light emit visible light upon de-excitation. The action of these materials is called **fluorescence.** In these materials, a photon of ultraviolet light excites the atom, boosting an electron to a higher energy state. In this upward quantum jump, the atom is likely to leapfrog over several intermediate energy states. So when the atom de-excites, it may make smaller jumps, emitting photons with less energy.

This excitation and de-excitation process is like leaping up a small staircase in a single bound, and then descending one or two steps at a time rather than leaping all the way down in a single bound. Photons of lower frequencies are emitted. Hence, ultraviolet light shining on the material causes it to glow an overall red, yellow, or

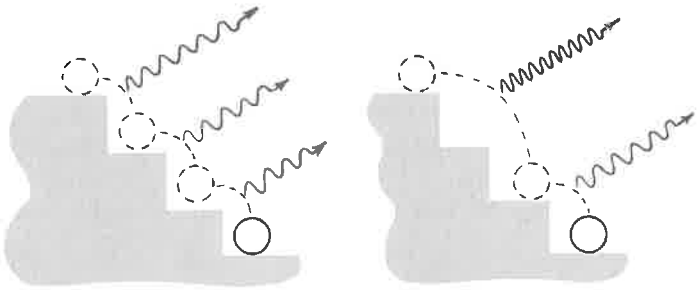

FIGURE 30.11

An excited atom may de-excite in several combinations of jumps.

whatever color is characteristic of the material. Fluorescent dyes are used in paints and fabrics to make them glow when bombarded with ultraviolet photons in sunlight. They can be spectacular when illuminated with an ultraviolet lamp.

Detergents that make the claim of cleaning your clothes "whiter than white" use the principle of fluorescence. Such detergents contain a fluorescent dye that converts the ultraviolet light in sunlight into blue visible light, so clothes washed in this way appear to reflect more blue light than they otherwise would. This makes the clothes appear whiter.[3]

The next time you visit a natural-science museum, go to the geology section and take in the exhibit of minerals illuminated with ultraviolet light (Figure 30.13). You'll notice that different minerals radiate various colors. This is to be expected because different minerals are composed of various elements, which, in turn, have a variety of sets of electron energy levels. Seeing the radiating minerals is a beautiful visual experience, which is even more fascinating when integrated with your knowledge of nature's submicroscopic happenings. High-energy ultraviolet photons strike the minerals, causing the excitation of atoms in the mineral structure. The frequencies of light that you see correspond to the tiny energy-level spacings as the energy cascades down. Every excited atom emits its characteristic frequencies, with no two different minerals emitting light of exactly the same color. Beauty is in both the eye and the mind of the beholder.

FIGURE 30.12

Crayons fluorescing in various colors under ultraviolet light.

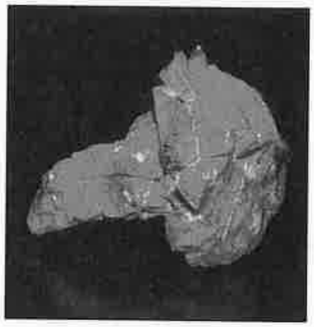

FIGURE 30.13

The rock contains the fluorescing minerals calcite and willemite, which, under ultraviolet light, are clearly seen as red and green, respectively.

CHECK POINT

Why would it be impossible for a fluorescent material to emit ultraviolet light when illuminated by infrared light?

Check Your Answer

Photon energy output would be greater than photon energy input, which would violate the law of conservation of energy.

Phosphorescence

When excited, certain crystals as well as some large organic molecules remain in a state of excitation for a prolonged period of time. Unlike what occurs in fluorescent materials, their electrons are boosted into higher orbits and become "stuck." As a result, there is a time delay between the processes of excitation and de-excitation. Materials that exhibit this peculiar property are said to have **phosphorescence.**

The element phosphorus is used in a variety of luminous materials, even toothbrushes, that are made to glow in the dark. Atoms or molecules in these materials are excited by incident visible light. Rather than de-exciting immediately, as fluorescent materials do, many of the atoms remain in a *metastable state*—a prolonged state of excitation—sometimes as long as several hours, although most de-excite rather quickly. If the source of excitation is removed—for instance, if the lights are put out—an afterglow occurs while millions of atoms spontaneously undergo gradual de-excitation. The afterglow of some phosphorescent light switches in the home may last more than an hour. Likewise for luminous clock dials, which are excited by visible light. Some older clock dials glow indefinitely in the dark, not because of a long time delay between excitation and de-excitation, but because they contain radium or some other radioactive material that continuously supplies energy to keep the excitation process

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- To make counterfeiting more difficult, many governments, including the U.S. government, use fluorescence. See this yourself by exposing any new-style U.S. currency to UV light. Near one end, a line will appear that cannot be seen with visible light. This fluorescent thread can be seen on the front and back of the bill.

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[3] Interestingly enough, the same detergents marketed in Mexico and some other countries are adjusted for a rosier, warmer effect.

going. Such dials are no longer common because of the potential harm of the radioactive material to the user, especially if in a wristwatch or pocket watch.[4]

Many living creatures—from bacteria to fireflies and larger animals, such as jellyfish—chemically excite molecules in their bodies that emit light. We say that such living things are *bioluminescent.* Under some conditions, certain fish become luminescent when they swim but remain dark when stationary. Schools of these fish hang motionless and are not seen, but when they are alarmed, they streak the depths with sudden light, creating a sort of deep-sea fireworks. The mechanism of bioluminescence is not well understood and is currently being researched.

CHECK POINT

- Distinguish between fluorescence and phosphorescence in terms of time.

Check Your Answer

Fluorescent materials emit light immediately after being excited. For phosphorescent materials there is a time delay between excitation and de-excitation.

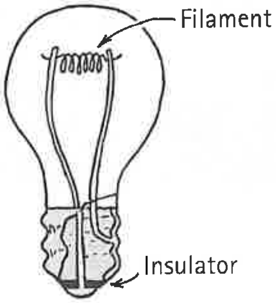

FIGURE 30.14

Simplified version of an incandescent bulb. A voltage source provides surges of energy to electrons in the high-resistance filament. A relatively small portion of this energy is converted to light.

fyi

- Although the incandescent bulb was not invented by Thomas Edison, he was the first to build one that outperformed other versions of the time and went on to invent an entire integrated system of electric lighting.

Lamps

INCANDESCENT LAMP

The common incandescent lamp consists of a glass enclosure with a filament of tungsten wire inside, through which an electric current is passed (Figure 30.14). The current typically heats the filament to 2000 K to 3300 K, well below tungsten's melting point of 3695 K. The hot filament emits a continuous spectrum, mostly in the infrared, with visible light as the smaller and useful part. The glass enclosure prevents oxygen in air from reaching the hot filament, which otherwise would be destroyed by rapid oxidation. Eventually, the filament fails anyway because of its gradual evaporation, which leads finally to a break in the filament and to the bulb "burning out."

Typically, argon is the gas inside the enclosure. If a small amount of a halogen element such as iodine is added to the interior, the evaporation of the tungsten is slowed and the bulb lasts longer. The action of the halogen requires that the whole bulb be hotter (don't touch a glowing halogen lamp!), so it is made smaller and usually encased in heat-resistant quartz. The halogen lamp may also be somewhat more efficient than the conventional incandescent lamp.

The efficiency of incandescent lightbulbs as visible light emitters is typically less than 10%. Hence, they are gradually being replaced by lamps that convert a greater percentage of electrical energy into visible light.

FLUORESCENT LAMP

The common fluorescent lamp consists of a cylindrical glass tube with electrodes at each end (Figure 30.15). In the lamp, as in the tube of a neon sign, electrons

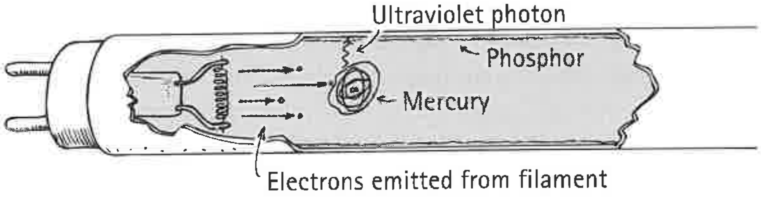

FIGURE 30.15

A fluorescent tube. Ultraviolet (UV) light is emitted by gas in the tube excited by an alternating electric current. The UV light, in turn, excites phosphors on the inner surface of the glass tube, which emit white light.

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[4] A radioactive form of hydrogen called *tritium,* however, can serve to keep watch dials illuminated harmlessly. This is because its radiation doesn't have enough energy to penetrate the metal or plastic of the watch case.

are boiled from one of the electrodes and forced to vibrate to and fro at high speeds within the tube by the ac voltage. The tube is filled with very-low-pressure mercury vapor added to argon. Mercury atoms are excited by the impact of the high-speed electrons. Much of the emitted light is in the ultraviolet region. This is the primary excitation process. The secondary process occurs when the ultraviolet light strikes *phosphors,* a powdery material on the inner surface of the tube. The phosphors are excited by the absorption of the ultraviolet photons and fluoresce, emitting a multitude of lower-frequency photons that combine to produce white light. Different phosphors can be used to produce different colors or "textures" of light.

FIGURE 30.16

This pair of 23-W CFLs emit as much light as a pair of 100-W incandescent lightbulbs operating at the same voltage.

COMPACT FLUORESCENT LAMP (CFL)

Miniaturize a fluorescent tube, wrap it into a coil, and outfit it with the same kind of plug a common incandescent lamp has, and you have a compact fluorescent lamp (CFL). Like the traditional tube-type fluorescent lamps, CFLs are more efficient than incandescent lamps, putting out about 4 times more light for the same power input. They fit into conventional lamp sockets and have lifetimes more than 10 times that of incandescent bulbs. As mentioned above and in Chapter 23, incandescent lamps are being replaced with more efficient lighting.

Like the tubular lamp, there are two main parts in a CFL: the gas-filled tube (mercury vapor mixed with argon) and the magnetic or electronic ballast. Whereas the ballasts used in early fluorescent tubes were magnetic, electronic ballasts are now much more common and don't flicker as the earlier ones did. The ballast provides the initial kick to start an arc discharge, boosts operating frequency via its transistors, and stabilizes current. Phosphors on the interior of the lamp can be chosen to produce not only different hues of white light but also colored light: yellow for outdoor lighting that does not attract insects; or long-wave ultraviolet for special effects.

A downside to the CFL is its mercury content, which poses environmental disposal problems. A more attractive alternative for lighting is the up-and-coming LED.

LIGHT-EMITTING DIODE (LED)

A diode is a two-terminal electronic device that permits a flow of charge in only one direction. Recall from Chapter 23 our brief discussion of a diode in converting ac to dc in electric circuits. Diodes serve a variety of functions, including regulation of voltage in circuits, signal amplification, measuring illumination, and converting light to electricity as photocells. One kind of diode design is the reverse of a photocell, in that an impressed voltage stimulates the emission of light! This is a light-emitting diode, LED. The first LEDs developed in the 1960s produced the red light common in instrument panels of the time. They let you know whether your DVD player is off or on. LEDs that emit a full range of colors were developed in the 1990s. Today, LEDs have advanced beyond indicator displays of electronic appliances and are common in traffic lights, automobile brake lights, airport runway lighting, warning lights on TV transmission towers, and even billboards. LEDs are compact, efficient, require no filament, are long-lasting (about 100 times longer than incandescent bulbs), and contain no harmful mercury.

When a diode collects light and produces electricity it's a solar cell. When the input is electricity and the output light, it's an LED. Just another nice symmetry in physics!

FIGURE 30.17

Evan holds two LEDs. The larger one, a GeoBulb (www.ccrane.com), uses less than 8 W and is the first direct replacement for a same-size incandescent 60-W bulb. The smaller LED, common in flashlights, emits 15 times as much light per watt as an incandescent bulb.

In one common LED design, a layer of a semiconductor that contains free electrons is deposited onto the surface of another semiconductor that contains energy "holes" that can accept the free electrons. An electrical barrier at the boundary of these two materials blocks electron flow (Figure 30.18a). But when an external voltage is applied, the barrier is overcome and energetic electrons cross over and "drop" into energy "holes." In a way similar to de-excitation, dropped electrons lose potential energy that is converted into quanta of light—photons (Fig. 30.18b). Just as a bowling ball rolling off of a table makes a loud "kerplunk" when it hits the floor, the analogous "kerplunk" of electrons in an LED is the emission of light. The drop in electron energy is converted to light.

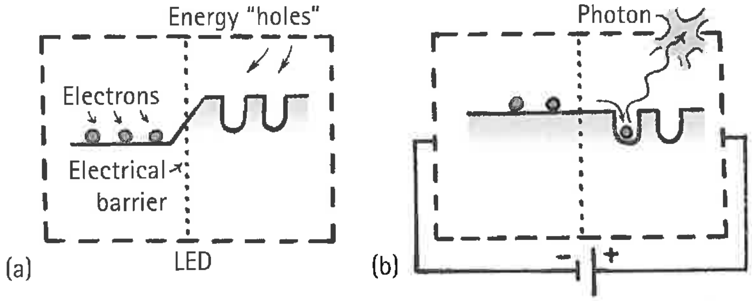

FIGURE 30.18

(a) An LED chip consists of two semiconductors, one with loose electrons, the other with "holes." (b) When a voltage is applied, electrons cross the barrier, occupy the holes, and emit light. The 0.25-mm square chip is surrounded by a transparent epoxy dome (not shown) of about 2 to 10 mm in diameter.

fyi

- One type of diode, the organic light emitting diode (OLED), is thin, lightweight, bright, and easy to manufacture. OLEDs may become important in the production of large flexible displays, wall decorations, and even illuminated clothing! This possibility gives new meaning to the phrase, "blue jeans!"

The elements used in the manufacture of an LED determine the depth of the energy "holes" and hence the color of the emitted photons. A greater energy drop releases light closer to blue; a lesser energy drop releases light toward the red. The huge commercial LED display in the billboard shown in the opening photographs of this chapter is composed of arrays of LEDs in sets of three. Each LED in a set can produce a single color: red, green, or blue. As with the displays of TV screens, each LED is activated to produce the desired mix of red, green, and blue. The full range of colors follows the color-mixing rules of Chapter 27. Then there are white-light LEDs that employ phosphors.

Lasers

The phenomena of excitation, fluorescence, and phosphorescence underlie the operation of a most intriguing instrument, the **laser** (light amplification by stimulated emission of radiation).[5] Although the first laser was invented in 1958, the concept of stimulated emission was predicted by Albert Einstein in 1917. To understand how a laser operates, we must first discuss *coherent light.*

Light emitted by a common lamp is incoherent; that is, photons of many frequencies and in many phases of vibration are emitted. The light is as incoherent as the footsteps on an auditorium floor when a mob of people are chaotically rushing about. Incoherent light is chaotic. A beam of incoherent light spreads out after a short distance, becoming wider and wider and less intense with increased distance.

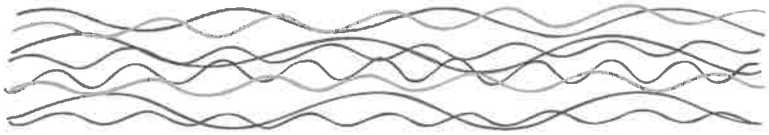

FIGURE 30.19

Incoherent white light contains waves of many frequencies (and of many wavelengths) that are out of phase with one another.

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[5] A word constructed from the initials of a phrase is called an *acronym.*

Even if the beam is filtered so that it consists of single-frequency waves (monochromatic light), it is still incoherent, because the waves are out of phase with one another.

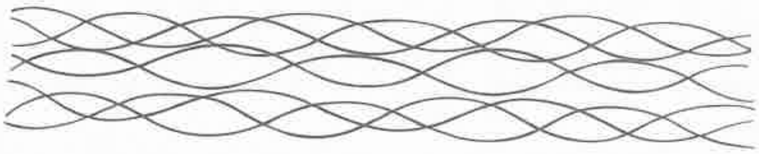

FIGURE 30.20

Light of a single frequency and wavelength still contains a mixture of phases.

A beam of photons having the same frequency, phase, and direction—that is, a beam of photons that are identical copies of one another—is said to be *coherent.* A laser emits a beam of coherent light that spreads and weakens very little.[6]

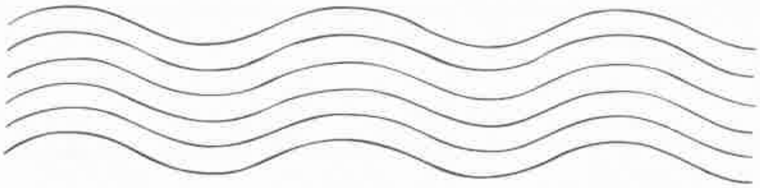

FIGURE 30.21

Coherent light. All the waves are identical, in phase, and in the same direction.

Every laser has a source of atoms called an active medium, which can be a gas, liquid, or solid (the first laser was a ruby crystal). The atoms in the medium are excited to metastable states by an external source of energy. When most of the atoms in the medium are excited, a single photon from an atom that undergoes de-excitation can start a chain reaction. This photon strikes another atom, stimulating it into emission, and so on, producing coherent light. Most of this light is initially moving in random directions. Light traveling along the laser axis, however, is reflected from mirrors coated to reflect light of the desired wavelength selectively. One mirror is totally reflecting, while the other is partially reflecting. The reflected waves reinforce each other after each round-trip reflection between the mirrors, thereby setting up a to-and-fro resonance condition wherein the light builds up to an appreciable intensity. The light that escapes through the more transparent-mirrored end makes up the laser beam. In addition to gas and crystal lasers, other types have joined the laser family: glass, chemical, liquid, and semiconductor lasers. Present models produce beams ranging from infrared through ultraviolet. Some models can be tuned to various frequency ranges.

A laser is not a source of energy. It is simply a converter of energy that takes advantage of the process of stimulated emission to concentrate a certain fraction of its energy (commonly 1%) into radiant energy of a single frequency moving in a single direction. Like all devices, a laser can put out no more energy than is put into it.

Lasers have found wide use in surgery. Lasers are also used in cutting and welding procedures, mainly where small parts are involved. They cut cleanly. Laser beams weld wires into microcircuits and repair damaged wires inside glass tubes. They are used in reading CDs and DVDs, and they create holograms. One day, they may trigger controlled fusion power. A huge application is in communications. Whereas radio wavelengths span hundreds of meters and television waves span many centimeters, wavelengths of laser light are measured in millionths of a centimeter. Correspondingly, laser-light frequencies are vastly greater than radio or television

A laser beam is not seen unless it scatters off something in the air. Like sunbeams or moonbeams, what you see are the particles in the scattering medium, not the beam itself. When the beam strikes a diffuse surface, part of it is scattered toward your eye as a dot.

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[6] The narrowness of a laser beam is evident when you see a lecturer produce a tiny red spot on a screen using a laser "pointer." Light from an intense laser pointed at the Moon has been reflected and detected back on Earth, revealing the Earth–Moon distance to an inch or so.

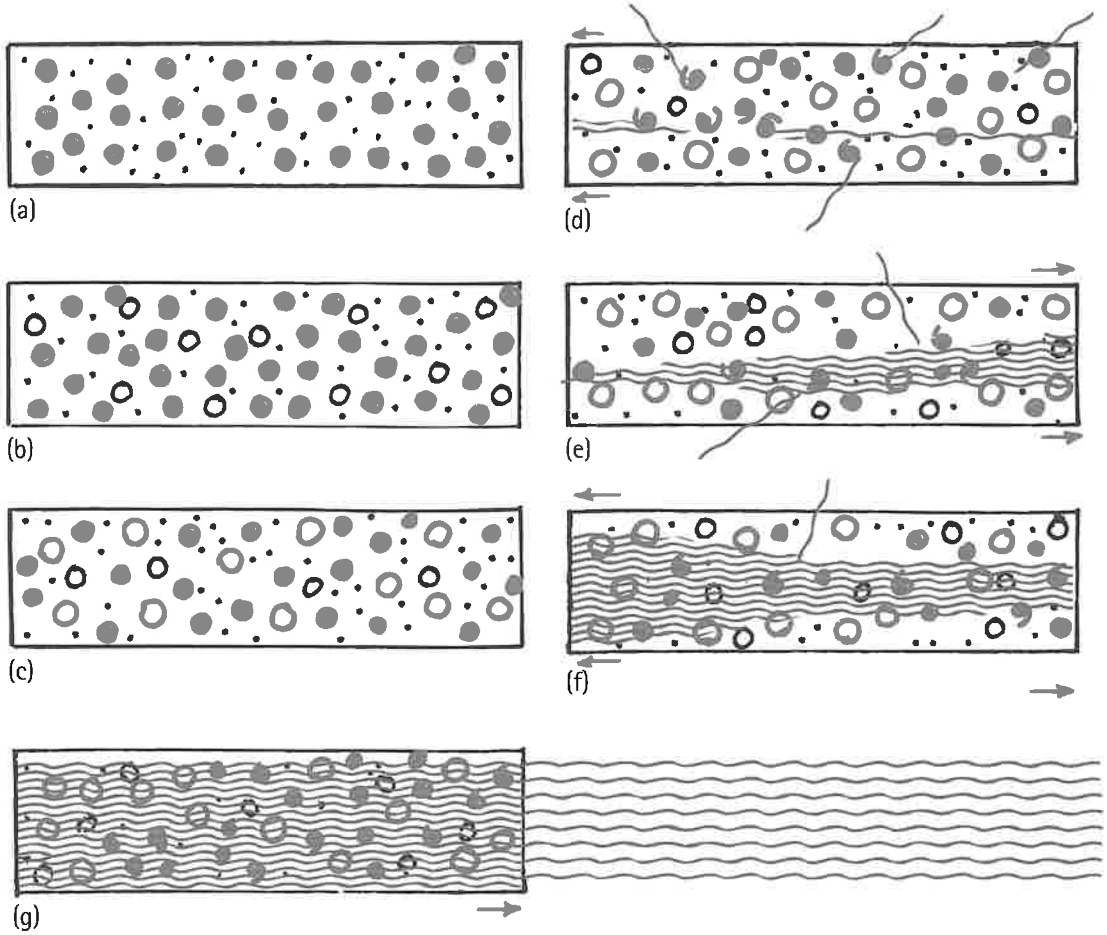


FIGURE 30.22

Laser action in a helium–neon laser.

(a) The laser consists of a narrow Pyrex tube that contains a low-pressure gas mixture consisting of 85% helium (small black dots) and 15% neon (large colored dots).

(b) When a high-voltage current zaps through the tube, it excites both helium and neon atoms to their usual higher states, and they immediately undergo de-excitation, except for one state in the helium that is characterized by a prolonged delay before de-excitation—a *metastable state.* Since this state is relatively stable, a sizable population of excited helium atoms (black open circles) is built up. These atoms wander about in the tube and act as an energy source for neon, which has an otherwise hard-to-come-by metastable state very close to the energy of the excited helium.

(c) When excited helium atoms collide with neon atoms in their lowest energy state (ground state), the helium gives up its energy to the neon, which is boosted to its metastable state (red open circles). The process continues, and the population of excited neon atoms soon outnumbers neon atoms in a lower-energy excited state. This inverted population is, in effect, waiting to radiate its energy.

(d) Some neon atoms eventually de-excite and radiate red photons in the tube. When this radiant energy passes other excited neon atoms, the latter are stimulated into emitting photons exactly in phase with the radiant energy that stimulated the emission. Photons pass out of the tube in irregular directions, giving it a red glow.

(e) Photons moving parallel to the axis of the tube are reflected from specially coated parallel mirrors at the ends of the tube. The reflected photons stimulate the emission of photons from other neon atoms, thereby producing an avalanche of photons having the same frequency, phase, and direction.

(f) The photons flash to and fro between the mirrors, becoming amplified with each pass.

(g) Some photons "leak" out of one of the mirrors, which is only partially reflecting. These make up the laser beam.

frequencies. As a result, laser light can transmit an enormous number of messages bunched into a very narrow band of frequencies. Communications can be carried in a laser beam directed through space, through the atmosphere, or through optical fibers (light pipes) that can be bent like cables.

The laser is at work at supermarket checkout counters, where code-reading machines scan the universal product code (UPC) symbol printed on packages and on the back cover of this book. Laser light is reflected from the bars and spaces and converted to an electric signal as the symbol is scanned. The signal rises to a high value when reflected from a bright space and falls to a low value when reflected from a dark bar. The information on the thickness and spacing of the bars is "digitized" (converted into the 1s and 0s of binary code) and processed by a computer.

Environmental scientists use lasers to measure and detect pollutants in exhaust gases. Different gases absorb light at characteristic wavelengths and leave their "fingerprints" on a reflected beam of laser light. The specific wavelength and amount of light absorbed are analyzed by a computer, which produces an immediate tabulation of the pollutants.

Lasers have ushered in a whole new technology, the promise of which we continually tap. The future for laser applications seems unlimited.

FIGURE 30.23
A helium–neon laser.

SUMMARY OF TERMS

Excitation The process of boosting one or more electrons in an atom or molecule from a lower to a higher energy level. An atom in an excited state will usually decay (de-excite) rapidly to a lower state by the emission of a photon. The energy of the photon is proportional to its frequency: $E = hf$.

Emission spectrum The distribution of wavelengths in the light from a luminous source.

Spectroscope An optical instrument that separates light into its constituent wavelengths in the form of spectral lines.

Incandescence The state of glowing while at a high temperature, caused by electrons bouncing around over dimensions larger than the size of an atom, emitting radiant energy in the process. The peak frequency of radiant energy is proportional to the absolute temperature of the heated substance:

$$\bar{f} \sim T$$

Absorption spectrum A continuous spectrum, like that of white light, interrupted by dark lines or bands that result from the absorption of light of certain frequencies by a substance through which the radiant energy passes.

Fluorescence The property of certain substances to absorb radiation of one frequency and to re-emit radiation of lower frequency. It occurs when an atom is boosted up to an excited state and loses its energy in two or more downward jumps to a lower energy state.

Phosphorescence A type of light emission that is the same as fluorescence except for a delay between excitation and de-excitation, which provides an afterglow. The delay is caused by atoms being excited to energy states that do not decay rapidly. The afterglow may last from fractions of a second to hours or even days, depending on the type of material, temperature, and other factors.

Laser (**l**ight **a**mplification by **s**timulated **e**mission of **r**adiation) An optical instrument that produces a beam of coherent monochromatic light.

REVIEW QUESTIONS

Light Emission

1. If electrons are made to vibrate to and fro at a few hundred thousand hertz, radio waves are emitted. What class of waves is emitted when electrons are made to vibrate to and fro at a few million billion hertz?
2. What does it mean to say an energy state is *discrete?*

Excitation

3. Relative to the atomic nucleus, which has more potential energy, electrons in inner electron shells or electrons in outer electron shells?
4. In a neon tube, what occurs immediately after an atom is excited?
5. What is the relationship between the *difference in energy* between energy levels and the *energy of the photon* that is emitted by a transition between those levels?
6. How is the *energy* of a photon related to its vibrational frequency?
7. Which has the higher *frequency,* red or blue light? Which has the greater *energy* per photon, red or blue light?
8. Can a neon atom in a glass tube be excited more than once? Explain.
9. What do the various colors displayed in the flame of a burning log represent?
10. Which puts out the greater percentage of its energy as light, an incandescent lamp or a mercury-vapor lamp?

Emission Spectra

11. What is a *spectroscope,* and what does it accomplish?

Incandescence

12. When a gas glows, discrete colors are emitted. When a solid glows, the colors are smudged. Why?
13. How is the peak frequency of emitted light related to the temperature of its incandescent source?

Absorption Spectra

14. How does an absorption spectrum differ in appearance from an emission spectrum?
15. What are Fraunhofer lines?
16. How can astrophysicists tell whether a star is receding or approaching Earth?

Fluorescence

17. Why is ultraviolet light, but not infrared light, effective in making certain materials fluoresce?

Phosphorescence

18. Distinguish between *fluorescence* and *phosphorescence.*
19. What is a *metastable state?*

Lamps

20. Why is argon, instead of air, used inside an incandescent bulb?
21. Distinguish between the primary and secondary excitation processes that occur in a fluorescent lamp.
22. How does the lifetime of a typical CFL compare with that of an incandescent bulb?
23. How does the lifetime of a typical LED compare with that of an incandescent bulb?

Lasers

24. Distinguish between *monochromatic light* and *coherent light.*
25. How does the avalanche of photons in a laser beam differ from the hordes of photons emitted by an incandescent lamp?

PROJECTS

1. Write a letter to Grandma to explain how light is emitted from lamps, flames, and lasers. Tell her why fluorescent dyes and paints are so impressively vivid when illuminated with an ultraviolet lamp. Go on to tell her about the higher efficiencies of CFLs and LEDs.
2. Borrow a diffraction grating from your physics instructor. The common kind looks like a photographic slide, and light passing through it or reflecting from it is diffracted into its component colors by thousands of finely ruled lines. Look through the grating at the light from a sodium-vapor street lamp. If it's a low-pressure lamp, you'll see the nice yellow spectral "line" that dominates sodium light (actually, it's two closely spaced lines). If the street lamp is round, you'll see circles instead of lines; if you look through a slit cut in cardboard or some similar material, you'll see lines. What happens with the now common high-pressure sodium lamps is more interesting. Because of the collisions of excited atoms, you'll see a smeared-out spectrum that is nearly continuous, almost like that of an incandescent lamp. Right at the yellow location, where you'd expect to see the sodium line, is a dark area. This is the sodium absorption band. It is due to the cooler sodium, which surrounds the high-pressure emission region. You should view this a block or so away so that the line, or circle, is small enough to allow the resolution to be maintained. Try this. It is very easy to see!

EXERCISES

1. Why is a gamma-ray photon more energetic than an X-ray photon?
2. Have you ever watched a fire and noticed that the burning of various materials often produces flames of different colors? Why is this so?
3. Green light is emitted when electrons in a substance make a particular energy-level transition. If blue light were instead emitted from the same substance, would it correspond to a greater or lesser change of energy in the atom?
4. Ultraviolet light causes sunburns, whereas visible light, even of greater intensity, does not. Why is this so?
5. If we double the frequency of light, we double the energy of each of its photons. If we instead double the wavelength of light, what happens to the photon energy?
6. Why doesn't a neon sign finally "run out" of atoms to excite and produce dimmer and dimmer light?
7. An investigator wishes spectral lines in a spectrum to be thin crescents. What change in the spectroscope will accomplish this?
8. If light were passed through a round hole instead of a thin slit in a spectroscope, how would the spectral "lines" appear? What is the drawback of a hole in comparison with a slit?
9. If we use a prism or a diffraction grating to compare the red light from a common neon tube and the red light from a helium–neon laser, what striking difference do we see?
10. What is the evidence for the claim that iron exists in the relatively cool outer layer of the Sun?
11. How might the Fraunhofer lines in the spectrum of sunlight that are due to absorption in the Sun's atmosphere be distinguished from those due to absorption by gases in Earth's atmosphere?

12. In what specific way does light from distant stars and galaxies tell astronomers that atoms throughout the universe have the same properties as those on Earth?

13. What difference does an astronomer see between the emission spectrum of an element in a receding star and a spectrum of the same element in the lab? (*Hint:* This relates to information in Chapter 19.)

14. A blue-hot star is about twice as hot as a red-hot star. But the temperatures of the gases in advertising signs are about the same, whether they emit red or blue light. What is your explanation?

15. Which has the greatest energy—a photon of infrared light, of visible light, or of ultraviolet light?

16. Does atomic excitation occur in solids as well as in gases? How does the radiant energy from an incandescent solid differ from the radiant energy emitted by an excited gas?

17. Low-pressure sodium-vapor lamps emit line spectra with well-defined wavelengths, but high-pressure sodium-vapor lamps emit light whose lines are more spread out. Relate this to the continuous smear of wavelengths emitted by solids.

18. A lamp filament is made of tungsten. Why do we get a continuous spectrum rather than a tungsten line spectrum when light from an incandescent lamp is viewed with a spectroscope?

19. How can a hydrogen atom, which has only one electron, have so many spectral lines?

20. Since an absorbing gas re-emits the light it absorbs, why are there dark lines in an absorption spectrum? That is, why doesn't the re-emitted light simply fill in the dark places?

21. If atoms of a substance absorb ultraviolet light and emit red light, what becomes of the "missing" energy?

22. (a) Light from an incandescent source is passed through sodium vapor and then examined with a spectroscope. What is the appearance of the spectrum? (b) The incandescent source is switched off and the sodium is heated until it glows. How does the spectrum of the glowing sodium compare with the previously observed spectrum?

23. Your friend reasons that if ultraviolet light can activate the process of *fluorescence,* infrared light ought to also. Your friend looks to you for approval or disapproval of this idea. What is your position?

24. When ultraviolet light falls on certain dyes, visible light is emitted. Why does this not happen when infrared light falls on these dyes?

25. Why are fabrics that fluoresce when exposed to ultraviolet light so bright in sunlight?

26. Why do different fluorescent minerals emit different colors when illuminated with ultraviolet light?

27. Some doors have spring-and-damper combinations so they close slowly when released. How is this similar to phosphorescence?

28. When a certain material is illuminated with visible light, electrons jump from lower to higher energy states in atoms of the material. When illuminated by ultraviolet light, atoms are ionized as some of them eject electrons. Why do the two kinds of illumination produce such different results?

29. To keep chickens warm in a chicken coop, why would a CFL be a poor choice compared with an incandescent bulb?

30. Why are LEDs the lamps of choice in hard-to-get-to places, such as high ceilings?

31. What color results when a red and a green LED shine together?

32. Cite at least two reasons for predicting that LEDs will emerge as more popular than CFLs.

33. The forerunner to the laser involved microwaves rather than visible light. What does *maser* mean?

34. The first laser consisted of a red ruby rod activated by a photoflash tube that emitted green light. Why would a laser composed of a green crystal rod and a photoflash tube that emits red light not work?

35. A laboratory laser has a power of only 0.8 mW, 8×10^{-4} W. Why does it seem more powerful than light from a 100-W lamp?

36. How do the avalanches of photons in a laser beam differ from the hordes of photons emitted by an incandescent lamp?

37. In the operation of a helium–neon laser, why is it important that the metastable state of helium be relatively long-lived? (What would be the effect of this state de-exciting too rapidly?) (Refer to Figure 30.22.)

38. In the operation of a helium–neon laser, why is it important that the metastable state in the helium atom closely match the energy level of a more-difficult-to-come-by metastable state in neon?

39. A friend speculates that scientists in a certain country have developed a laser that produces far more energy than is put into it and asks for your response. What is your response?

40. A laser cannot produce more energy than is put into it. A laser can, however, produce pulses of light with more power output than the power input required to run the laser. Explain.

41. In the equation $\bar{f} \sim T$, what do the symbols f and T represent?

42. We know that an incandescent lamp filament at 2500 K radiates white light. Does the lamp filament also radiate energy when it is at room temperature?

43. We know that the Sun radiates energy. Does Earth similarly radiate energy? If so, what is different about their radiations?

44. Since every object has some temperature, every object radiates energy. Why, then, can't we see objects in the dark?

45. If we continue heating a piece of initially room-temperature metal in a dark room, it will begin to glow visibly. What will be its first visible color, and why?

46. We can heat a piece of metal to red-hot and then to white-hot. Can we heat it until the metal glows blue-hot?

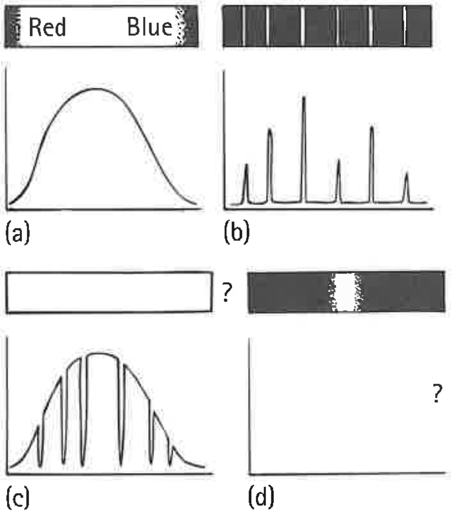
47. How do the surface temperatures of reddish, bluish, and whitish stars compare?

48. If you see a red-hot star, you can be certain that its peak intensity is in the infrared region. Why is this?

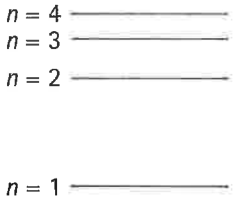
49. If you see a "violet-hot" star, you can be certain its peak intensity is in the ultraviolet range. Why is this?

50. We perceive a "green-hot" star not as green but as white. Why? (*Hint:* Consider the radiation curve back in Figures 27.7 and 27.8, and in Figure 30.7.)

51. Sketch (a) below shows a radiation curve of an incandescent solid and its spectral pattern as produced with a spectroscope. Sketch (b) shows the "radiation curve" of an excited gas and its emission spectral pattern. Sketch (c) shows the curve produced when a cool gas is between an incandescent source and the viewer; the corresponding spectral pattern is left as an exercise for you to construct. Sketch (d) shows the spectral pattern of an incandescent source as seen through a piece of green glass; you are to sketch in the corresponding radiation curve.



52. Consider just four of the energy levels in a certain atom, as shown in the diagram. How many spectral lines will result from all possible transitions among these levels? Which transition corresponds to the highest-frequency light emitted? To the lowest-frequency light emitted?



53. An electron de-excites from the fourth quantum level in the diagram of Exercise 52 to the third and then directly to the ground state. Two photons are emitted. How does the sum of their frequencies compare with the frequency of the single photon that would be emitted by de-excitation from the fourth level directly to the ground state?

54. For the transitions described in the previous exercise, is there any relationship among the wavelengths of the emitted photons?

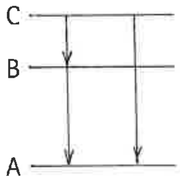
55. Suppose the four energy levels in Exercise 52 were somehow evenly spaced. How many spectral lines would result?

PROBLEM

In the diagram, the energy difference between states A and B is twice the energy difference between states B and C. In a transition (quantum jump) from C to B, an electron emits a photon of wavelength 600 nm.

a. What is the wavelength emitted when the photon jumps from B to A?

b. When it jumps from C to A?



CHAPTER 30 ONLINE RESOURCES

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Interactive Figures

- 30.2, 30.5, 30.7, 30.8, 30.10

Tutorial

- Light and Spectroscopy

Quizzes

Flashcards

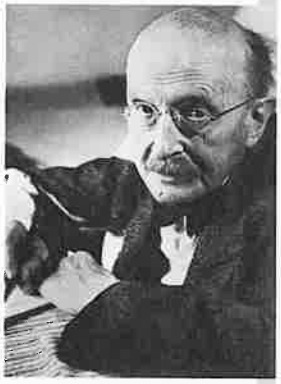
Links

31 Light Quanta

1 Phil Wolf, co-author of *Problem Solving in Conceptual Physics,* demonstrates the photoelectric effect by directing light of different frequencies onto a photocell and measuring the energies of ejected electrons. 2 Busy physicists at a control center at the CERN Super Proton Synchrotron in France, on the Swiss border near Geneva. The control center combines the control rooms of the laboratory's eight accelerators. 3 Anne Cox, co-author of *Physlet Quantum Physics,* aligns an optical tweezer with her students at Eckerd College in Florida.

As a youth in Germany, Max Planck was a gifted musician. He sang, played various instruments, and composed songs and operas. Instead of studying music, however, he chose to study physics, earning his doctorate in1879 when he was 21. At the time, the two great theories of physics being actively pursued were thermodynamics, the study of heat, and electromagnetism, the study of radiation. Little did Planck guess that in trying to blend these two fields, he would usher in a whole new physics of the 20th century—*quantum mechanics.*

In 1900, perplexing questions about the radiation of thermal energy remained unanswered. The way in which the energy of thermal radiation is distributed over different frequencies had been carefully measured, but no one had been able to provide a theory to account for the results. In hopes of providing a theoretical answer, Planck, at the "advanced" age of 42, made a hypothesis that he called "an act of despair." He proposed that when a warm object emits radiant energy, it loses energy not continuously but in discrete amounts, or lumps, which he called *quanta.* Moreover, he postulated that the quantum of energy that is radiated is proportional to the frequency of the radiation. With this theory he could explain how the energy in thermal radiation is distributed over different frequencies. Five years later Einstein (then 26) took the next step, proposing that not only is energy added to light in quantum units but light itself exists as quantum lumps, or "corpuscles," later named photons.



In recognition for introducing the quantum, Planck was awarded the Nobel Prize in Physics in 1918.

Interestingly, Planck himself never accepted the photon idea. In 1912, in a classic put-down, Planck wrote that because of other achievements, Einstein deserved membership in the Prussian Academy of Sciences, despite having gone astray in proposing a corpuscle of light.

Planck had twin daughters, Emma and Grete, and two sons, Karl and Erwin. During the First World War his younger son, Erwin, was taken prisoner by the French in 1914, and his older son, Karl, was killed in action at Verdun. Soon after and two years apart, both daughters died while giving birth. Planck endured these losses stoically.

When Hitler came to power in 1933, Planck at first hoped that Nazism would be a temporary affliction, but eventually he made his distaste for the Nazis plain, and in 1938 he resigned the presidency of the Prussian Academy in protest. In 1944, at the height of World War II, Planck's house in Berlin was completely destroyed by Allied bombing raids. In the same year his son Erwin was implicated in the attempt made on Hitler's life in the famed July 20 plot. Although it is said that Erwin could have been spared had Planck joined the Nazi Party, Planck took a stand and refused to join. Erwin was hanged in early 1945, which devastated his elderly father. Planck died two years later in 1947, at age 89.

Birth of the Quantum Theory

The classical physics that we have so far studied deals with two categories of phenomena: particles and waves. In accord with Newton's laws, "particles" are tiny objects like bullets that have mass and travel through space in straight lines unless a force acts upon them. Likewise, "waves," like those of sound or in the ocean, are phenomena that *extend* in space. When a wave travels through an opening or around a barrier, the wave diffracts and different parts of the wave interfere. Therefore, particles and waves are easy to distinguish from each other. In fact, they have properties that are mutually exclusive. Nonetheless, the question of how to classify light was a mystery for centuries.

One of the early theories about the nature of light is that of Plato, who lived in the 5th and 4th centuries BC. Plato thought that light consisted of streamers emitted by the eye. Euclid, who lived roughly a century later, also held this view. On the other hand, the Pythagoreans believed that light emanated from luminous bodies in the form of very fine particles, while Empedocles, a predecessor of Plato, taught that light is composed of high-speed waves of some sort. For more than 2000 years, the questions remained unanswered. Does light consist of waves or particles?

In 1704, Isaac Newton described light as a stream of particles. He held this view despite his knowledge of what we now call polarization and despite his experiment with light reflecting from glass plates, in which he noticed fringes of brightness and darkness (Newton's rings). He knew that his particles of light had to have certain wave properties too. Christian Huygens, a contemporary of Newton, advocated a wave theory of light.

With all this history as background, Thomas Young, in 1801, performed the "double-slit experiment," which seemed to prove, finally, that light is a wave phenomenon. This view was reinforced in 1862 by Maxwell's prediction that light carries energy in oscillating electric and magnetic fields. Twenty-five years later, Heinrich Hertz used sparking electric circuits to demonstrate the reality of electromagnetic waves (of radio frequency). As mentioned above, Max Planck in 1900 hypothesized that radiant energy was emitted in discrete bundles, each of which he called a **quantum.** According to Planck, the energy in each energy bundle is proportional to the frequency of radiation ($E \sim f$, which we treated in the previous chapter). His hypothesis began a revolution of ideas that has completely changed the way we think about the physical world. Planck's hypothesis was given credence in 1905 when Albert Einstein published a Nobel Prize-winning paper that challenged the wave theory of light by arguing that light interacts with matter, not in continuous waves, as Maxwell envisioned, but in tiny packets of energy as Planck had suggested, which we now call *photons.* Broadly speaking, the body of laws developed from 1900 to the late 1920s that describe all quantum phenomena of the microworld is known as **quantum physics.**

Quantization and Planck's Constant

Quantization, the idea that the natural world is granular rather than continuously smooth, is certainly not a new idea to physics. Matter is quantized; the mass of a bar of gold, for example, is equal to some whole-number multiple of the mass of a single gold atom. Electricity is quantized, as electric charge is always some whole-number multiple of the charge of a single electron.

Quantum physics states that in the microworld of the atom, the amount of energy in any system is quantized—not all values of energy are possible. This is analogous to saying a campfire can only be so hot. It might burn at 450°C or it might burn at 451°C, but can't burn at 450.5°C. Believe it? Well, you shouldn't, for as far as our macroscopic thermometers can measure, a campfire can burn at any temperature as long as it's above the minimum temperature that is required for combustion. But the energy of the campfire, interestingly enough, is the composite energy of a great number and a great variety of elemental units of energy. A simpler example is the energy in a beam of laser light, which is a whole-number multiple of a single lowest value of energy—one quantum. The quanta of light, and of electromagnetic radiation in general, are the photons. (The plural of quantum is *quanta.*)

Recall, from the previous chapter, that the energy of a photon is given by $E = hf$, where h is **Planck's constant** (the single number that results when the energy of a photon is divided by its frequency).[1] We shall see that Planck's constant is a fundamental constant of nature that serves to set a lower limit on the smallness of things. It ranks with the velocity of light and Newton's gravitational constant as a basic constant of nature, and it appears again and again in quantum physics. The equation $E = hf$ gives the smallest amount of energy that can be converted to light with frequency f. The radiation of light is not emitted continuously but is emitted as a stream of photons, with each photon throbbing at a frequency f and carrying an energy hf.

The equation $E = hf$ tells us why microwave radiation can't do the damage to molecules in living cells that ultraviolet light and X-rays can. Electromagnetic radiation interacts with matter only in discrete bundles of photons. So the relatively low frequency of microwaves ensures low energy per photon. Ultraviolet radiation, on the other hand, can deliver about a million times more energy to a molecule because the frequency of ultraviolet radiation is about a million times greater than the frequency of microwaves. X-rays, with even higher frequencies, can deliver even more.

Quantum physics tells us that the physical world is a coarse, grainy place. The "common-sense" world described by classical physics seems smooth and continuous because quantum graininess is on a very small scale compared with the sizes of things in the familiar world. Planck's constant is small in terms of familiar units. But you don't have to enter the quantum world to encounter graininess underlying apparent smoothness. For example, the blending areas of black, white, and gray in the photograph of Max Planck on the opening page of this chapter and other photographs in this book do not look smooth at all when viewed through a magnifying glass. With magnification, you can see that a printed photograph consists of many tiny dots. In a similar way, we live in a world that is a blurred image of the grainy world of atoms.

Light quanta, electrons, and other particles all behave as if they were lumps in some respects and waves in others.

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[1] Planck's constant, h, has the numerical value 6.6×10^{34} J·s.

CHECK POINT

1. What does the term *quantum* mean?
2. How much total energy is in a monochromatic beam composed of *n* photons of frequency *f*?

Check Your Answers

1. A *quantum* is the smallest elemental unit of a quantity. Radiant energy, for example, is composed of many quanta, each of which is called a *photon*. So the more photons in a beam of light, the more energy in that beam.
2. The energy in a monochromatic beam of light containing n quanta is $E = nhf$.

Photoelectric Effect

In the latter part of the 19th century, several investigators noticed that light was capable of ejecting electrons from various metal surfaces. This is the **photoelectric effect,** for many years used in electric eyes, in the photographer's light meter, and, before digital, in the sound tracks of motion pictures. An extension of the photoelectric effect is today's photovoltaic electric cells and their potential for being a major power source.

An arrangement for observing the photoelectric effect is shown in Figure 31.1. Light shining on the negatively charged, photosensitive metal surface liberates electrons. The liberated electrons are attracted to the positive plate and produce a measurable current. If we instead charge this plate with just enough negative charge that it repels electrons, the current can be stopped. We can then calculate the energies of the ejected electrons from the easily measured potential difference between the plates.

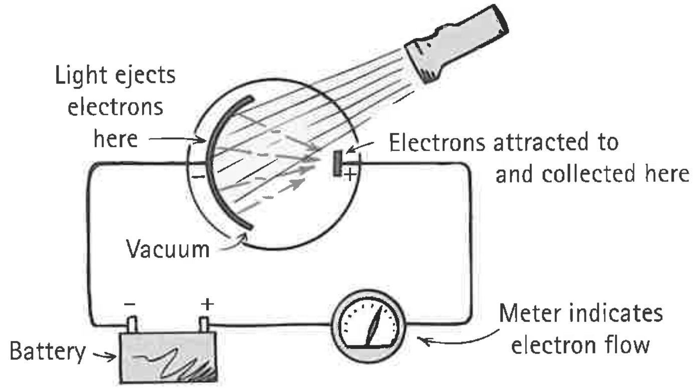

FIGURE 31.1

INTERACTIVE FIGURE

An apparatus used for observing the photoelectric effect. Reversing the polarity and stopping the electron flow provides a way to measure the energy of the electrons.

The photoelectric effect was not particularly surprising to early investigators. The ejection of electrons could be accounted for by classical physics, which pictures the incident light waves building an electron's vibration up to greater and greater amplitudes until it finally breaks loose from the metal surface, just as water molecules break loose from the surface of heated water. It should take considerable time for a weak source of light to give electrons in a metal enough energy to make them boil off the surface. Instead, it was found that electrons are ejected as soon as the light is turned on—but not as many are ejected as with a strong light source. Careful examination of the photoelectric effect led to several observations that were quite contrary to the classical wave picture:

1. The time lag between turning on the light and the ejection of the first electrons was unaffected by the brightness or frequency of the light.

2. The effect was easy to observe with violet or ultraviolet light but not with red light.
3. The rate at which electrons were ejected was proportional to the brightness of the light.
4. The maximum energy of the ejected electrons was unaffected by the brightness of the light. However, there were indications that the electron's energy did depend on the frequency of the light.

The lack of any appreciable time lag was especially difficult to understand in terms of the wave picture. According to the wave theory, an electron in dim light should, after some delay, accumulate sufficient vibrational energy to fly out, while an electron in bright light should be ejected almost immediately. However, this didn't occur. It was not unusual to observe an electron being ejected immediately, even under the dimmest light. The observation that the brightness of light in no way affected the energies of ejected electrons was also perplexing. The stronger electric fields of brighter light did not cause electrons to be ejected at greater speeds. More electrons were ejected in brighter light, but not at greater speeds. A weak beam of ultraviolet light, on the other hand, produced a smaller number of ejected electrons but at much higher speeds. This was most puzzling.

Einstein produced the answer in 1905, the same year he explained Brownian motion and set forth his theory of special relativity. His clue was Planck's quantum theory of radiation. Planck had assumed that the emission of light in quanta was due to restrictions on the vibrating atoms that produced the light. That is, he assumed that energy in *matter* is quantized, but that radiant energy is continuous. Einstein, on the other hand, attributed quantum properties to light itself and viewed radiation as a hail of particles. This particle aspect is emphasized when we speak of photons (by analogy with electrons, protons, and neutrons). One photon is completely absorbed by each electron ejected from the metal. The absorption is an all-or-nothing process and is immediate, so there is no delay as "wave energies" build up.

A light wave has a broad front, and its energy is spread out along this front. For the light wave to eject a single electron from a metal surface, all its energy would somehow have to be concentrated on that one electron. But this is as improbable as an ocean wave hurling a boulder far inland with an energy equal to that of the whole wave. Therefore, instead of thinking of light encountering a surface as a continuous train of waves, the photoelectric effect suggests we conceive of light encountering a surface or any detector as a succession of particles—photons. The number of photons in a light beam affects the brightness of the *whole beam,* whereas the frequency of the light controls the energy of each *individual photon.*

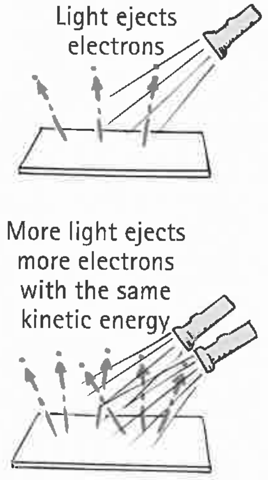

FIGURE 31.2

The photoelectric effect depends on intensity.

Electrons are held in a metal by attractive electrical forces. A minimum energy, called the *work function,* W_0, is required for an electron to leave the surface. A low-frequency photon with energy less than W_0 won't produce electron ejection. Only a photon with energy greater than W_0 results in the photoelectric effect. Thus the energy of the incoming photon will be equal to the outgoing kinetic energy of the electron plus the energy required to get it out of the metal, W_0.

Experimental verification of Einstein's explanation of the photoelectric effect was demonstrated 11 years later by the American physicist Robert Millikan. Interestingly, Millikan spent some 10 years trying to disprove Einstein's theory of the photon only to become convinced of it as a result of his own experiments, which won him a Nobel Prize. Every aspect of Einstein's interpretation was confirmed, including the direct proportionality of photon energy to frequency. It was for this (and not for his theory of relativity) that Einstein received his Nobel Prize. Astoundingly, it was not until 1923 and the discovery of other quantum evidence that physicists generally accepted the reality of the photon.

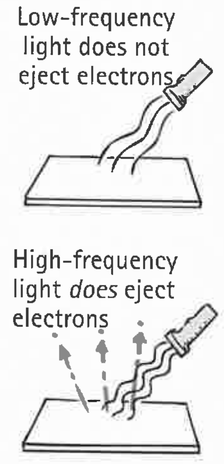

FIGURE 31.3

The photoelectric effect depends on frequency.

The photoelectric effect proves conclusively that light has particle properties. We cannot conceive of the photoelectric effect on the basis of waves. On the other hand, we have seen that the phenomenon of interference demonstrates convincingly that light has wave properties. We cannot conceive of interference in terms of particles. In classical physics this is contradictory. From the point of view of quantum physics, light has properties resembling both. It is "just like a wave" or "just like a particle," depending on the particular experiment. So we think of light as both, as a wave–particle. How about "wavicle"? Quantum physics calls for a new way of thinking.

CHECK POINT

1. Will brighter light eject more electrons from a photosensitive surface than dimmer light of the same frequency?
2. Will high-frequency light eject a greater number of electrons than low-frequency light?

Check Your Answers

1. Yes. The number of ejected electrons depends on the number of incident photons.
2. Not necessarily. The energy (not the number) of ejected electrons depends on the frequency of the illuminating photons. A bright source of blue light, for example, may eject more electrons at a lower energy than a dim violet source.

Wave–Particle Duality

The wave and particle nature of light is evident in the formation of optical images. We understand the photographic image produced by a camera in terms of light waves, which spread from each point of the object, refract as they pass through the lens system, and converge to focus on the light-sensitive recording medium—either photographic film or, in a digital camera, an electronic detector. The path of light from the object through the lens system and to the focal plane can be calculated using methods developed from the wave theory of light.

But now consider carefully the way in which an image is formed on photographic film. The film consists of an emulsion that contains grains of silver halide crystal, each grain containing about 10^{10} silver atoms. Each photon that is absorbed gives up its energy, hf, to a single grain in the emulsion. This energy activates surrounding crystals in the entire grain and is used in development to complete the photochemical process. Many photons activating many grains produce the usual photographic exposure. When a photograph is taken with exceedingly feeble light, we find that the image is built up by individual photons that arrive independently and are seemingly random in their distribution. We see this strikingly illustrated in Figure 31.4, which shows how an exposure progresses photon by photon.

Double-Slit Experiment

Let's return to Thomas Young's double-slit experiment, which we discussed in terms of waves in Chapter 29. Recall that when we pass monochromatic light through a pair of closely spaced thin slits, we produce an interference pattern (Figure 31.5). Now let's consider the experiment in terms of photons. Suppose we dim our light source so that, in effect, only one photon at a time reaches the barrier with the thin slits. If film behind the barrier is exposed to the light for a very short time, the film gets exposed as simulated in Figure 31.6a. Each spot represents the place where the film has been exposed by a photon. If the light is allowed to expose

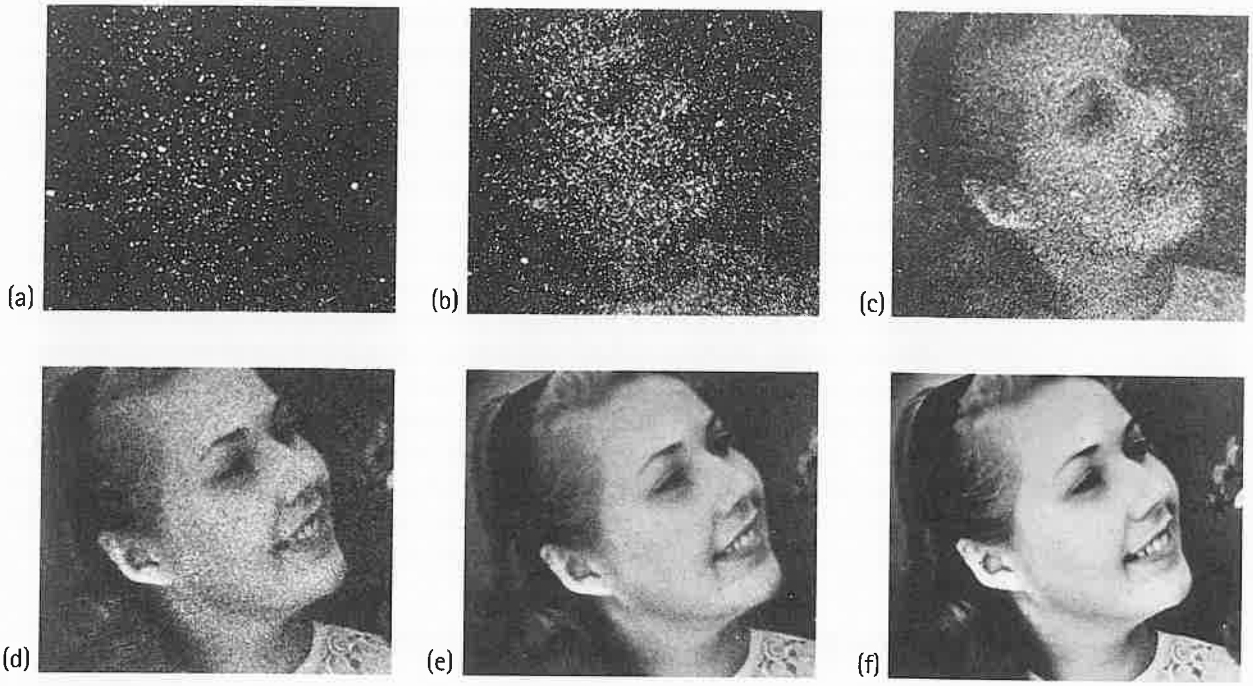

FIGURE 31.4

Stages of film exposure reveal the photon-by-photon production of a photograph. The approximate numbers of photons at each stage are (a) 3×10^3, (b) 1.2×10^4, (c) 9.3×10^4, (d) 7.6×10^5, (e) 3.6×10^6, and (f) 2.8×10^7.

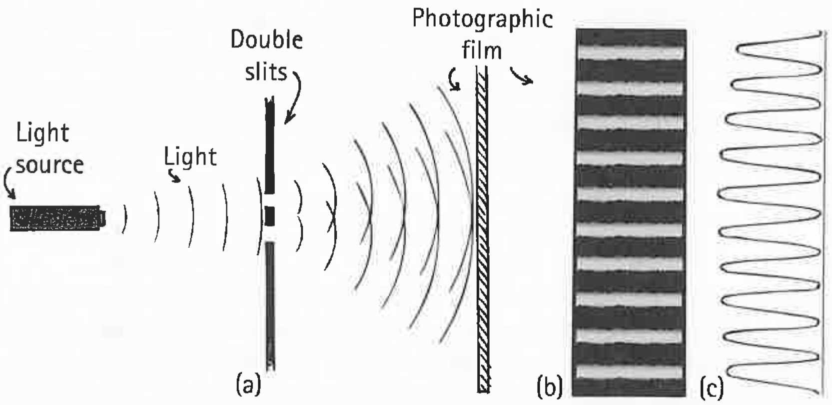

FIGURE 31.5

(a) Arrangement for double-slit experiment. (b) Photograph of interference pattern. (c) Graphic representation of pattern.

the film for a longer time, a pattern of fringes begins to emerge, as in Figures 31.6b and 31.6c. This is quite amazing! Spots on the film are seen to progress, photon by photon, to form the same interference pattern characterized by waves!

If we cover one slit so that photons striking the photographic film can pass only through a single slit, the tiny spots on the film accumulate to form a single-slit

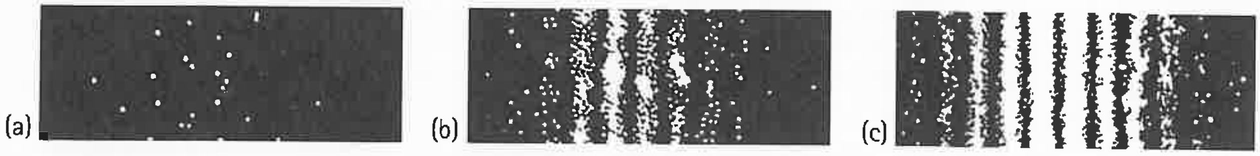

FIGURE 31.6

INTERACTIVE FIGURE

Stages of two-slit interference pattern. The pattern of individually exposed grains progresses from (a) 28 photons to (b) 1000 photons to (c) 10,000 photons. As more photons hit the screen, a pattern of interference fringes appears.

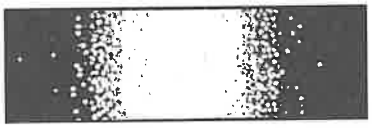

FIGURE 31.7
Single-slit diffraction pattern.

Light travels as a wave and hits like a particle.

diffraction pattern (Figure 31.7). We find that photons hit the film at places they would not hit if both slits were open! If we think about this classically, we are perplexed and may ask how photons passing through the single slit "know" that the other slit is covered and therefore fan out to produce the wide single-slit diffraction pattern. Or, if both slits are open, how do photons traveling through one slit "know" that the other slit is open and avoid certain regions, proceeding only to areas that will ultimately fill to form the fringed double-slit interference pattern?[2] The modern answer is that the wave nature of light is not some average property that appears only when many photons act together. Each single photon has wave properties as well as particle properties. But the photon displays different aspects at different times. *A photon behaves as a particle when it is being emitted by an atom or absorbed by photographic film or other detectors, and behaves as a wave in traveling from a source to the place where it is detected.* So the photon strikes the film as a particle but travels to its position as a wave that interferes constructively. The fact that light exhibits both wave and particle behavior was one of the interesting surprises of the early 20th century. Even more surprising was the discovery that objects with mass also exhibit a dual wave–particle behavior.

Particles as Waves: Electron Diffraction

Louis de Broglie
(1892–1987)

If a photon of light has both wave and particle properties, why can't a material particle (one with mass) also have both wave and particle properties? This question was posed by the French physicist Louis de Broglie while he was still a graduate student in 1924. His answer constituted his doctoral thesis in physics and later earned him the Nobel Prize in physics. According to de Broglie, every particle of matter is somehow endowed with a wave to guide it as it travels. Under the proper conditions, then, every particle will produce an interference or diffraction pattern. Each body—whether an electron, a proton, an atom, a mouse, you, a planet, a star—has a wavelength that is related to its momentum by

$$\text{Wavelength} = \frac{h}{\text{momentum}}$$

where h is Planck's constant. A body of large mass and ordinary speed has such a small wavelength that interference and diffraction are negligible; rifle bullets fly straight and do not pepper their targets far and wide with detectable interference patches.[3] But, for smaller particles, such as electrons, diffraction can be appreciable.

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[2] From a pre-quantum point of view, this wave–particle duality is indeed mysterious. This leads some people to believe that quanta have some sort of consciousness, with each photon or electron having "a mind of its own." The mystery, however, is like beauty. It is in the mind of the beholder rather than in nature itself. We conjure models to understand nature and, when inconsistencies arise, we sharpen or change our models. The wave–particle duality of light doesn't fit a model built on classical ideas. An alternate model is that quanta have minds of their own. Another model is quantum physics. In this book, we subscribe to the latter.

[3] A bullet of mass 0.02 kg traveling at 330 m/s, for example, has a de Broglie wavelength of

$$\frac{h}{mv} = \frac{6.6 \times 10^{-34}\,\text{J}\cdot\text{s}}{(0.02\text{ kg})(330\text{ m/s})} = 10^{-34}\text{m}$$

an incredibly small size, a million million million millionth the size of a hydrogen atom. An electron traveling at 2% the speed of light, on the other hand, has a wavelength 10^{-10}m, which is equal to the diameter of the hydrogen atom. Diffraction effects for electrons are measurable, whereas diffraction effects for bullets are not.

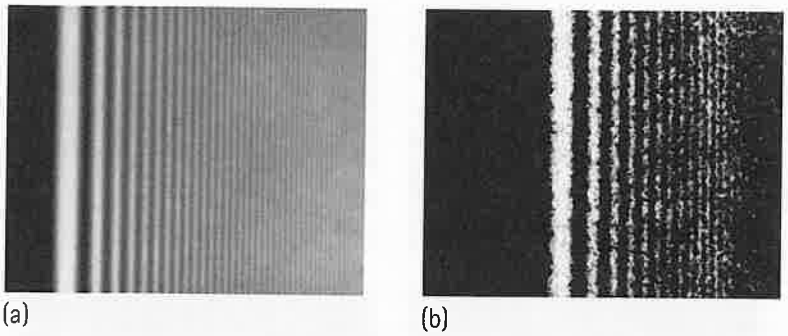


FIGURE 31.8
Fringes produced by the diffraction of (a) light and (b) an electron beam.

Both a beam of electrons and a beam of photons can be diffracted in the same way, as is evident in Figure 31.8. Beams of electrons directed through double slits also exhibit interference patterns. The double-slit experiment discussed in the previous section can be performed with electrons as well as with photons. For electrons, the apparatus is more complex, but the procedure is essentially the same. The intensity of the source can be reduced to direct electrons one at a time through a double-slit arrangement, producing the same remarkable results as with photons. Like photons, electrons strike the screen as particles, but the *pattern* of arrival is wavelike. The angular deflection of electrons to form the interference pattern agrees perfectly with calculations using de Broglie's equation for the wavelength of an electron.

FIGURE 31.9
An electron microscope makes practical use of the wave nature of electrons. The wavelength of electron beams is typically thousands of times shorter than the wavelength of visible light, so the electron microscope is able to distinguish detail not visible with optical microscopes.

In Figure 31.11, we see another example of electron diffraction, using a standard electron microscope. The electron beam of very low current density is directed through an electrostatic biprism that diffracts the beam. A pattern of fringes produced by individual electrons builds up step-by-step and is displayed on a TV monitor. The image is gradually filled by electrons to produce the interference pattern customarily associated with waves. The wave–particle duality is not restricted to photons and electrons. Neutrons, protons, whole atoms, and, to an immeasurable degree, even high-speed rifle bullets exhibit a duality of particle and wave behavior.

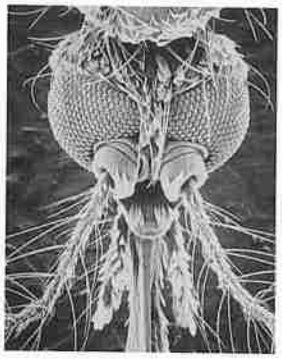


FIGURE 31.10
Detail of the head of a female mosquito as seen with a scanning electron microscope at a "low" magnification of 200×.

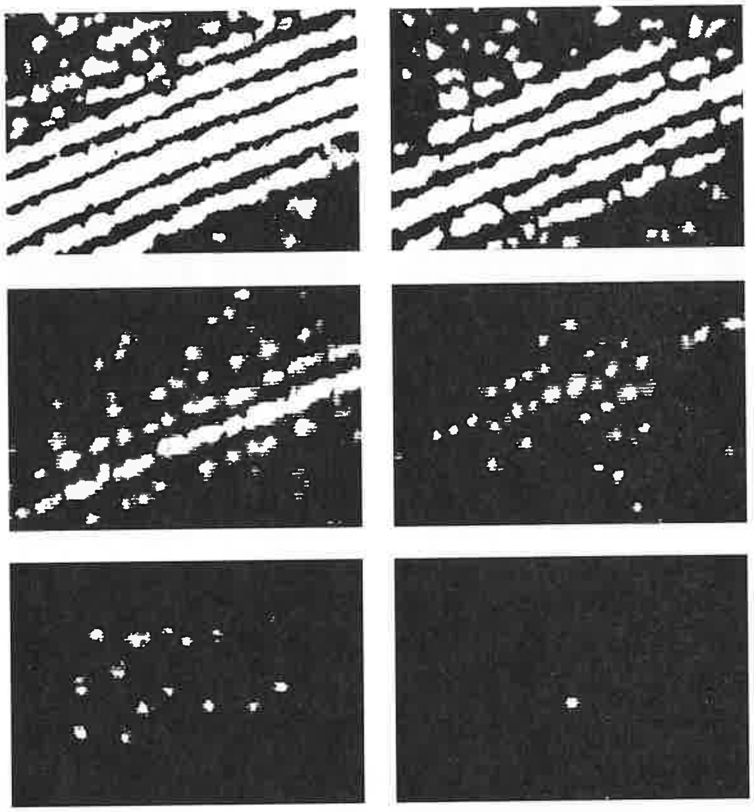
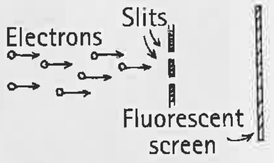


FIGURE 31.11

Electron interference patterns filmed from a TV monitor, showing the diffraction of a very low intensity electron-microscope beam through an electrostatic biprism.

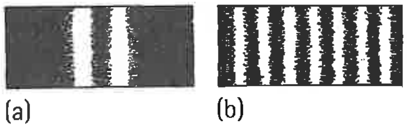
CHECK POINT

1. If electrons behaved only like particles, what pattern would you expect on the screen after the electrons passed through the double slits?
2. We don't notice the de Broglie wavelength for a pitched baseball. Is this because the wavelength is very large or because it is very small?
3. If an electron and a proton have the same de Broglie wavelength, which particle has the greater speed?



Check Your Answers

1. If electrons behaved only like particles, they would form two bands, as indicated in (a). Because of their wave nature, they actually produce the pattern shown in (b).



2. We don't notice the wavelength of a pitched baseball because it is extremely small—on the order of 10^{-20} times smaller than the atomic nucleus.
3. The same wavelength means that the two particles have the same momentum. This means that the less massive electron must travel faster than the heavier proton.

Uncertainty Principle

The wave–particle duality of quanta has inspired interesting discussions about the limits of our ability to accurately measure the properties of small objects. The discussions center on the idea that the act of measuring something affects the quantity being measured.

For example, we know that, if we place a cool thermometer in a cup of hot coffee, the temperature of the coffee is altered as it gives heat to the thermometer. The measuring device alters the quantity being measured. But we can correct for these errors in measurement if we know the initial temperature of the thermometer, the masses and specific heats involved, and so forth. Such corrections fall well within the domain of classical physics—these are *not* the uncertainties of quantum physics. Quantum uncertainties stem from the wave nature of matter. A wave, by its very nature, occupies some space and lasts for some time. It cannot be squeezed to a point in space or limited to a single instant of time, for then it would not be a wave. This inherent "fuzziness" of a wave gives a fuzziness or uncertainty of measurement at the quantum level. Innumerable experiments have shown that any measurement that in any way probes a system necessarily disturbs the system by at least one quantum of action, h—Planck's constant. So any measurement that involves interaction between the measurer and what is being measured is subject to this minimum inaccuracy.

We distinguish between observing and probing. Consider a cup of coffee on the other side of a room. If you passively glance at it and see steam rising from it, this act of "measuring" involves no physical interaction between your eyes and the coffee. Your glance neither adds nor subtracts energy from the coffee. You can assert that it's hot with no *probing.* Placing a thermometer in it is a different story. You physically interact with the coffee and thereby subject it to alteration. The quantum contribution to this alteration, however, is completely dwarfed by classical uncertainties and is negligible. Quantum uncertainties are significant only in the atomic and subatomic realm.

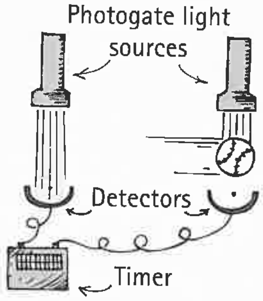


FIGURE 31.12

The ball's speed is measured by dividing the distance between the photogates by the time difference between crossing the two light paths. Photons hitting the ball alter its motion much less than the motion of an oil supertanker would be altered by a few fleas bumping into it.

Compare the acts of making measurements of a pitched baseball and of an electron. You can measure the speed of a pitched baseball by having it fly through a pair of photogates that are a known distance apart (Figure 31.12). The ball is timed as it interrupts beams of light in the gates. The accuracy of the ball's measured speed has to do with uncertainties in the measured distance between the gates and in the timing mechanisms. Interactions between the macroscopic ball and the photons it encounters are insignificant. But not so in the case of measuring submicroscopic things like electrons. Even a single photon bouncing off an electron appreciably alters the motion of the electron—and in an unpredictable way. If you wish to observe an electron and determine its whereabouts with light, the wavelength of the light would have to be very short. You fall into a dilemma. Light of a short wavelength, which can "see" the tiny electron better, corresponds to a large quantum of energy, which, in turn, greatly alters the electron's state of motion. If, on the other hand, you use a long wavelength that corresponds to a smaller quantum of energy, the change you induce to the electron's state of motion will be smaller, but the determination of its position by means of the coarser wave will be less accurate. The act of observing something as tiny as an electron probes the electron and, in so doing, produces a considerable uncertainty in either its position or its motion. Although this uncertainty is completely negligible for measurements of position and motion regarding everyday (macroscopic) objects, it is a predominant fact of life in the atomic domain.

Werner Heisenberg (1901–1976)

The uncertainty of measurement in the atomic domain, which was first stated mathematically by the German physicist Werner Heisenberg, is called the **uncertainty principle.** It is a fundamental principle in quantum mechanics. Heisenberg found that when the uncertainties in the measurement of momentum and position for a particle are multiplied together, the product must be equal to or greater than Planck's constant, h, divided by 2π, which is represented as $\hbar$ (called *h-bar*).[4] We can state the uncertainty principle in a simple formula:

$$\Delta p \Delta x \geq \hbar$$

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[4] Quantum physicist Ken Ford celebrates $\hbar$ on the number plate of his Honda Civic Hybrid (back on page 353).

The Δ here means "uncertainty of": Δp is the uncertainty of momentum (the symbol for momentum is conventionally p), and Δx is the uncertainty of position. The product of these two uncertainties must be equal to or greater than ($\geq$) the size of $\hbar$. For minimum uncertainties, the product will equal $\hbar$; the product of larger uncertainties will be greater than $\hbar$. But in no case can the product of the uncertainties be less than $\hbar$. The significance of the uncertainty principle is that, even in the best of conditions, the lower limit of uncertainty is $\hbar$. This means that if we wish to know the momentum of an electron with great accuracy (small Δp), the corresponding uncertainty in position will be large. Or if we wish to know the position with great accuracy (small Δx), the corresponding uncertainty in momentum will be large. The sharper one of these quantities is, the less sharp is the other.[5]

You can never change only one thing! Every equation reminds us of this—you can't change a term on one side without affecting the other side.

The uncertainty principle operates similarly with energy and time. We cannot measure a particle's energy with complete precision in an infinitesimally short span of time. The uncertainty in our knowledge of energy, ΔE, and the duration taken to measure the energy, Δt, are related by the expression[6]

$$\Delta E \Delta t \geq \hbar$$

The greatest accuracy we can ever hope to attain is that case in which the product of the energy and time uncertainties equals $\hbar$. The more accurately we determine the energy of a photon, an electron, or a particle of whatever kind, the more uncertain we will be of the time during which it has that energy.

The uncertainty principle is relevant only to quantum phenomena. The inaccuracies in measuring the position and momentum of a baseball due to quantum effects are completely negligible. But the inaccuracies in measuring the position and momentum of an electron are far from negligible. This is because the uncertainties in the measurements of these subatomic quantities are comparable to the magnitudes of the quantities themselves.[7]

There is a danger in applying the uncertainty principle to areas outside of quantum mechanics. Some people conclude from statements about the interaction between the observer and the observed that the universe does not exist "out there," independent of all acts of observation, and that reality is created by the observer. Others interpret the uncertainty principle as nature's shield of forbidden secrets. Some critics of science use the uncertainty principle as evidence that science itself is uncertain. The reality of the universe (whether observed or not), nature's secrets, and the uncertainties of science have very little to do with Heisenberg's uncertainty principle. The profundity of the uncertainty principle has to do with the unavoidable interaction between nature at the atomic level and the means by which we probe it.

[5] In a hypothetical purely classical world, $\hbar$ would be zero and the uncertainties of both position and momentum could be arbitrarily small. In the real world, Planck's constant is greater than zero, and we cannot, in principle, simultaneously know both quantities with certainty.

[6] We can see that this is consistent with the uncertainty in momentum and position. Recall that $\Delta\text{momentum} = \text{force} \times \Delta\text{time}$ and that $\Delta\text{energy} = \text{force} \times \Delta\text{distance}$. Then,

$$\begin{aligned} \hbar &= \Delta\text{momentum} \times \Delta\text{distance} \\ &= (\text{force} \times \Delta\text{distance}) \times \Delta\text{time} \\ &= \Delta\text{energy} \times \Delta\text{time} \end{aligned}$$

[7] The uncertainties in measurements of momentum, position, energy, or time that are related to the uncertainty principle for a pitched baseball are only 1 part in about 10 million billion billion billion (10^{-34}). Quantum effects are negligible even for the most sluggish bacterium, where the uncertainties are about 1 part in a billion (10^{-9}). Quantum effects become evident for atoms, where the uncertainties can be as large as 100%. For electrons moving in an atom, quantum uncertainties dominate, and we are in the full-scale quantum realm.

CHECK POINT

1. Is Heisenberg's uncertainty principle applicable to the practical case of using a thermometer to measure the temperature of a glass of water?
2. A Geiger counter measures radioactive decay by registering the electrical pulses produced in a gas tube when high-energy particles pass through it. The particles emanate from a radioactive source—say, radium. Does the act of measuring the decay rate of radium alter the radium or its decay rate?
3. Can the quantum principle that we cannot observe something without changing it be reasonably extrapolated to support the claim that you can make a stranger turn around and look at you by staring intently at his back?

Check Your Answers

1. No. Although we probably subject the temperature of water to a change by the act of probing it with a thermometer, especially one appreciably colder or hotter than the water, the uncertainties that relate to the precision of the thermometer are quite within the domain of classical physics. The role of uncertainties at the subatomic level is inapplicable here.
2. Not at all, because the interaction involved is between the Geiger counter and the particles, not between the Geiger counter and the radium. It is the behavior of the particles that is altered by measurement, not the radium from which they emanate. See how this relates to the next question.
3. No. Here we must be careful in defining what we mean by *observing*. If our observation involves probing (giving or extracting energy), we indeed change to some degree that which we observe. For example, if we shine a light source onto the person's back, our observation consists of probing, which, however slight, physically alters the configuration of atoms on his back. If he senses this, he may turn around. But simply staring intently at his back is observing in the passive sense. The light you receive (or block by blinking, for example) has already left his back. So whether you stare, squint, or close your eyes completely, you in no physical way alter the atomic configuration on his back. Shining a light or otherwise probing something is not the same thing as passively looking at something. A failure to make the simple distinction between *probing* and *passive observation* is at the root of much nonsense that is said to be supported by quantum physics. Better support for the above claim would be positive results from a simple and practical test, rather than the assertion that it rides on the hard-earned reputation of quantum theory.

Complementarity

The realm of quantum physics can seem confusing. Light waves that interfere and diffract deliver their energy in packages of quanta—particles. Electrons that move through space in straight lines and experience collisions as if they were particles distribute themselves spatially in interference patterns as if they were waves. In this confusion, there is an underlying order. The behavior of light and electrons is confusing in the same way! Light and electrons both exhibit wave and particle characteristics.

The Danish physicist Niels Bohr, one of the founders of quantum physics, formulated an explicit expression of the wholeness inherent in this dualism. He called his expression of this wholeness **complementarity.** As Bohr expressed it, quantum phenomena exhibit complementary (mutually exclusive) properties—appearing

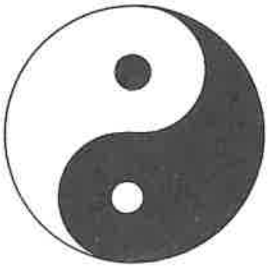


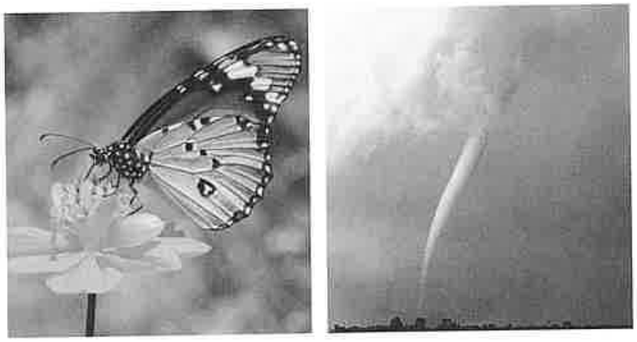
FIGURE 31.13
Opposites are seen to complement one another in the yin–yang symbol of Eastern cultures.

either as particles or as waves—depending on the type of experiment conducted. Experiments designed to examine individual exchanges of energy and momentum reveal particle-like properties, while experiments designed to examine spatial distribution of energy reveal wavelike properties. The wavelike and particle-like properties of light complement one another—both are necessary for the understanding of "light." Which part is emphasized depends on what question one presents to nature.

Complementarity is not a compromise, and it doesn't mean that the whole truth about light lies somewhere in between particles and waves. It's rather like viewing the sides of a crystal. What you see depends on what facet you look at, which is why light, energy, and matter appear to be behaving as quanta in some experiments and as waves in others.

The idea that opposites are components of a wholeness is not new. Ancient Eastern cultures incorporated it as an integral part of their worldview. This is demonstrated in the yin–yang diagram of T'ai Chi Tu (Figure 31.13). One side of the circle is called *yin* (black), and the other side is called *yang* (white). Where there is yin, there is yang. Only the union of yin and yang forms a whole. Where there is low, there is also high. Where there is night, there is also day. Where there is birth, there is also death. A whole person integrates yin (feminine traits, right brain, emotion, intuition, darkness, cold, wetness) with yang (masculine traits, left brain, reason, logic, light, heat, dryness). Each has aspects of the other. For Niels Bohr, the yin–yang diagram symbolized the principle of complementarity. In later life, Bohr wrote broadly on the implications of complementarity. In 1947, when he was knighted for his contributions to physics, he chose for his coat of arms the yin–yang symbol.

Predictability and Chaos



We can make predictions about an orderly system when we know the initial conditions. For example, we can state precisely where a launched rocket will land, where a given planet will be at a particular time, or when an eclipse will occur. These are examples of events in the Newtonian macroworld. Similarly, in the quantum microworld, we can predict where an electron is *likely* to be in an atom and the *probability* that a radioactive particle will decay in a given time interval. Predictability in orderly systems, both Newtonian and quantum, depends on knowledge of initial conditions.

Some systems, however, whether Newtonian or quantum, are not orderly—they are inherently unpredictable. These are called "chaotic systems." Turbulent water flow is an example. No matter how precisely we know the initial conditions of a piece of floating wood as it flows downstream, we cannot predict its location later downstream. A feature of chaotic systems is that slight differences in initial conditions result in wildly different outcomes later. Two identical pieces of wood just slightly apart at one time may be vastly far apart soon thereafter.

Weather is chaotic. Small changes in one day's weather can produce big (and largely unpredictable) changes a week later. Meteorologists try their best, but they are bucking the hard fact of chaos in nature. This barrier to accurate prediction first led the meteorologist Edward Lorenz to ask, "Does the flap of a butterfly's wings in Brazil set off a tornado in Texas?" We now talk about the *butterfly effect* when we are dealing with situations in which very small effects can amplify into very big effects.

Interestingly, chaos is not all hopeless unpredictability. Even in a chaotic system there can be patterns of regularity. There is *order in chaos*. Scientists have learned how to treat chaos mathematically and how to find the parts of it that are orderly. Artists seek patterns in nature in a different way. Both scientists and artists look for the connections in nature that were always there but are not yet put together in our thinking.

SUMMARY OF TERMS

Quantum (*pl.* quanta) From the Latin word *quantus,* meaning "how much." A quantum is an elemental unit of a quantity, a discrete amount of something. One quantum of electromagnetic energy is called a photon.

Quantum physics The physics that describes the microworld, where many quantities are granular (in units called *quanta*), not continuous, and where particles of light *(photons)* and particles of matter (such as electrons) exhibit wave as well as particle properties.

Planck's constant A fundamental constant, h, that relates the energy of light quanta to their frequency:

$$h = 6.6 \times 10^{-34}\,\text{J}\cdot\text{s}$$

Photoelectric effect The emission of electrons from a metal surface when light shines upon it.

Uncertainty principle The principle, formulated by Werner Heisenberg, stating that Planck's constant, h, sets a limit on the accuracy of measurement. According to the uncertainty principle, it is not possible to measure exactly both the position and the momentum of a particle at the same time, nor the energy and the time during which the particle has that energy.

Complementarity The principle, enunciated by Niels Bohr, stating that the wave and particle aspects of both matter and radiation are necessary, complementary parts of the whole. Which part is emphasized depends on what experiment is conducted (i.e., on what question one puts to nature).

REVIEW QUESTIONS

Birth of the Quantum Theory

1. Which theory of light, the wave theory or the particle theory, did the findings of Young, Maxwell, and Hertz support?

2. Did Einstein's photon explanation of the photoelectric effect support the wave theory or the particle theory of light?

3. What exactly did Max Planck consider quantized, the energy of vibrating atoms or the energy of light itself?

Quantization and Planck's Constant

4. What is a quantum of light called?

5. In the formula $E = hf$, does f stand for wave frequency, as defined in Chapter 19?

6. Which has the lower energy quanta—red light or blue light? Radio waves or X-rays?

Photoelectric Effect

7. Which are more successful in dislodging electrons from a metal surface—photons of violet light or photons of red light? Why?

8. Why won't a very bright beam of red light impart more energy to an ejected electron than a feeble beam of violet light?

Wave–Particle Duality

9. Why do photographs in a book or magazine look grainy when magnified?

10. Does light behave primarily as a wave or as a particle when it interacts with the crystals of matter in photographic film?

Double-Slit Experiment

11. Does light travel from one place to another in a wavelike or a particle-like way?

12. Does light interact with a detector in a wavelike or a particle-like way?

13. When does light behave as a wave? When does it behave as a particle?

Particles as Waves: Electron Diffraction

14. What evidence can you cite for the wave nature of particles?

15. When electrons are diffracted through a double slit, do they hit the screen in a wavelike way or in a particle-like way? Is the pattern of hits wavelike or particle-like?

Uncertainty Principle

16. In which of the following are quantum uncertainties significant: measuring simultaneously the speed and location of a baseball; of a spitball; of an electron?

17. What is the uncertainty principle with respect to momentum and position?

18. If measurements show a precise position for an electron, can those measurements show precise momentum also? Explain.

19. If measurement shows a precise value for the energy radiated by an electron, can that measurement show a precise time for this event as well? Explain.

20. What is the distinction in this book between passively and actively observing an event?

Complementarity

21. What is the principle of complementarity?

22. Cite evidence that the idea of opposites as components of a wholeness preceded Bohr's principle of complementarity.

EXERCISES

1. What does it mean to say that something is quantized?
2. Distinguish between *classical physics* and *quantum physics.*
3. In the previous chapter, we learned the formula $E \sim f$. In this chapter, we learned the formula $E = hf$. Explain the difference between these two formulas. What is h?
4. The frequency of violet light is about twice that of red light. How does the energy of a violet photon compare with the energy of a red photon?
5. Which has more energy—a photon of visible light or a photon of ultraviolet light?
6. We speak of photons of red light and photons of green light. Can we speak of photons of white light? Why or why not?
7. Which laser beam carries more energy per photon—a red beam or a green beam?
8. If a beam of red light and a beam of blue light have exactly the same energy, which beam contains the greater number of photons?
9. One of the technical challenges facing the original developers of color television was the design of an image tube (camera) for the red portion of the image. From an energy point of view, why was finding a material that would respond to red light more difficult than finding materials to respond to green and blue light?
10. Phosphors on the inside of fluorescent lamps convert ultraviolet light to visible light. Why are there no substances that convert visible light to ultraviolet light?
11. Silver bromide (AgBr) is a light-sensitive substance used in some types of photographic film. To cause exposure of the film, it must be illuminated with light having sufficient energy to break apart the molecules. Why do you suppose this film may be handled without exposure in a darkroom illuminated with red light? How about blue light? How about very bright red light relative to very dim blue light?
12. Sunburn produces cell damage in the skin. Why is ultraviolet radiation capable of producing this damage, while visible radiation, even if more intense, is not?
13. In the photoelectric effect, does brightness or frequency determine the kinetic energy of the ejected electrons? Which determines the number of the ejected electrons?
14. A very bright source of red light has much more energy than a dim source of blue light, but the red light has no effect in ejecting electrons from a certain photosensitive surface. Why is this so?
15. Why are ultraviolet photons more effective at inducing the photoelectric effect than photons of visible light?
16. Why does light striking a metal surface eject only electrons, not protons?
17. Does the photoelectric effect depend on the wave nature or the particle nature of light?
18. Explain how the photoelectric effect is used to open automatic doors when someone approaches.
19. Explain briefly how the photoelectric effect is used in the operation of at least two of the following: an electric eye, a photographer's light meter, the sound track of a pre-digital motion picture.
20. If you shine an ultraviolet light on the metal ball of a negatively charged electroscope (shown in Exercises 11 and 12 in Chapter 22), it will discharge. But if the electroscope is positively charged, it won't discharge. Can you venture an explanation?
21. Discuss how the reading of the meter in Figure 31.1 will vary as the photosensitive plate is illuminated by light of various colors at a given intensity and by light of various intensities of a given color.
22. Does the photoelectric effect *prove* that light is made of particles? Do interference experiments *prove* that light is composed of waves? (Is there a distinction between what something *is* and how it *behaves?*)
23. Does Einstein's explanation of the photoelectric effect invalidate Young's explanation of the double-slit experiment? Explain.
24. The camera that took the photograph of the woman's face (Figure 31.4) used ordinary lenses that are well known to refract waves. Yet the step-by-step formation of the image is evidence of photons. How can this be? What is your explanation?
25. What evidence can you cite for the wave nature of light? For the particle nature of light?
26. When does a photon behave like a wave? When does it behave like a particle?
27. Light has been argued to be a wave and then a particle, and then back again. Does this indicate that light's true nature probably lies somewhere between these two models?
28. What laboratory device utilizes the wave nature of electrons?
29. How might an atom obtain enough energy to become ionized?
30. When an X-ray photon of a certain frequency hits an electron and gives it energy, make a hypothesis about the frequency of the photon that "leaves the scene" of the collision. (This phenomenon is called the *Compton effect.*)
31. A hydrogen atom and a uranium atom move at the same speed. Which possesses more momentum? Which has the longer wavelength?
32. If a cannonball and a BB have the same speed, which has the longer wavelength?
33. An electron and a proton travel at the same speed. Which has more momentum? Which has the longer wavelength?
34. One electron travels twice as fast as another. Which has the longer wavelength?
35. Does the de Broglie wavelength of a proton become longer or shorter as its velocity increases?
36. We don't notice the wavelength of moving matter in our common experience. Is this because the wavelength is extraordinarily large or extraordinarily small?
37. What principal advantage does an electron microscope have over an optical microscope?
38. Would a beam of protons in a "proton microscope" exhibit greater or less diffraction than electrons of the same speed in an electron microscope? Defend your answer.
39. Suppose nature were entirely different so that an infinite number of photons would be needed to make up even the tiniest amount of radiant energy, the wavelength of material particles was zero, light had no particle properties,

and matter had no wave properties. This would be the classical world described by the mechanics of Newton and the electricity and magnetism of Maxwell. What would be the value of Planck's constant for such a world with no quantum effects?

40. Suppose that you lived in a hypothetical world in which you'd be knocked down by a single photon, in which matter would be so wavelike that it would be fuzzy and hard to grasp, and in which the uncertainty principle would impinge on simple measurements of position and speed in a laboratory, making results irreproducible. In such a world, how would Planck's constant compare with the accepted value?

41. Comment on the idea that the theory one accepts determines the meaning of one's observations and not vice versa.

42. A friend says, "If an electron is not a particle, then it must be a wave." What is your response? (Do you hear "either-or" statements like this often?)

43. Consider one of the many electrons on the tip of your nose. If somebody looks at it, will its motion be altered? How about if it is viewed with one eye closed? With two eyes open, but crossed? Does Heisenberg's uncertainty principle apply here?

44. Does the uncertainty principle tell us that we can never know anything for certain?

45. Do we inadvertently alter the realities that we attempt to measure in a public opinion survey? Does Heisenberg's uncertainty principle apply here?

46. If the behavior of a system is measured exactly for some period of time and is understood, does it follow that the future behavior of that system can be exactly predicted? (Is there a distinction between properties that are *measurable* and properties that are *predictable?*)

47. When checking the pressure in tires, some air escapes. Why does Heisenberg's uncertainty principle not apply here?

48. If a butterfly causes a tornado, does it make sense to eradicate butterflies? Defend your answer.

49. We hear the expression "taking a quantum leap" to describe large changes. Is the expression appropriate? Defend your answer.

50. To measure the exact age of Old Methuselah, the oldest living tree in the world, a Nevada professor of dendrology, aided by an employee of the U.S. Bureau of Land Management, cut the tree down in 1965 and counted its rings. Is this an extreme example of altering that which you measure or an example of arrogant and criminal stupidity?

PROBLEMS

1. A typical wavelength of infrared radiation emitted by your body is 25 mm (2.5×10^{-2} m). Show that the energy per photon of such radiation is about 8.0×10^{-24} J.

2. Consider the de Broglie wavelength of an electron that strikes the back face of one of the early models of a TV screen at 1/10 the speed of light. Show that the electron wavelength is 2.4×10^{-11} m.

• **3.** You decide to roll a 0.1-kg ball across the floor so slowly that it will have a small momentum and a large de Broglie wavelength. If you roll it at 0.001 m/s, what is its wavelength? How does this compare with the de Broglie wavelength of the high-speed electron in the previous problem?

CHAPTER 31 ONLINE RESOURCES

Interactive Figures

- 31.1, 31.6

Quizzes

Flashcards

Links

PART SIX MULTIPLE-CHOICE PRACTICE EXAM

Choose the BEST answer to the following:

1. Which of these does NOT belong in the family of electromagnetic waves?
   (a) Light.
   (b) Sound.
   (c) Radio waves.
   (d) X-rays.
2. Light that is not transmitted by opaque materials is
   (a) converted to internal energy in the material.
   (b) mainly reflected.
   (c) mainly refracted.
   (d) transmitted at a lower frequency.
3. When the shadow of the Moon falls on Earth, we have a
   (a) lunar eclipse.
   (b) solar eclipse.
   (c) solar eclipse if it's daytime and lunar eclipse if it's nighttime.
   (d) very dangerous event.
4. Black is the combination of
   (a) all the colors together.
   (b) two or more appropriate colors.
   (c) light when a prism is held upside down.
   (d) None of these.
5. To say that a rose petal is red is to say that it
   (a) absorbs red.
   (b) reflects red.
   (c) emits red.
   (d) transmits red.
6. The color of light most intense in the solar radiation curve is
   (a) infrared.
   (b) red.
   (c) yellow-green.
   (d) violet.
7. When red and blue light are overlapped, the color produced is
   (a) magenta.
   (b) yellow.
   (c) cyan.
   (d) white.
8. The complementary color of blue is
   (a) magenta.
   (b) yellow.
   (c) cyan.
   (d) white.
9. The blueness of the daytime sky is due mostly to light
   (a) absorption.
   (b) transmission.
   (c) reflection.
   (d) scattering.
10. The redness of a sunrise or sunset is due mostly to light that hasn't been
    (a) absorbed.
    (b) transmitted.
    (c) scattered.
    (d) polarized.
11. The greenish blue of ocean water mostly involves light that is
    (a) absorbed.
    (b) reflected.
    (c) scattered.
    (d) refracted.
12. Your distance of your image behind a plane mirror is equal to
    (a) half your height.
    (b) half your distance from the mirror.
    (c) your distance in front of the mirror.
    (d) more than your distance in front of the mirror.
13. Refraction occurs when a wave crosses a boundary and changes
    (a) speed and direction.
    (b) intensity.
    (c) frequency.
    (d) amplitude.
14. When white light passes through a prism, the light that bends more than green is
    (a) red.
    (b) yellow.
    (c) blue.
    (d) None of these.
15. A rainbow is the result of light in raindrops that undergoes
    (a) internal reflection.
    (b) dispersion.
    (c) refraction.
    (d) All of these.
16. When a diver points a flashlight upward toward the surface of the water at an angle 20° from the normal, the beam of light
    (a) totally internally reflects.
    (b) passes into the air above.
    (c) is absorbed.
    (d) None of these.
17. A real image can be cast on a screen by a
    (a) converging lens.
    (b) diverging lens.
    (c) Either of these.
    (d) Neither of these.
18. Huygens' principle for light is primarily described by
    (a) waves.
    (b) rays.
    (c) particles.
    (d) photons.
19. A diffraction grating relies on light
    (a) interference.
    (b) amplitudes.
    (c) variations in brightness.
    (d) being composed of photons.
20. When light undergoes interference, it can sometimes
    (a) build up to more than the sum of amplitudes.
    (b) cancel completely.
    (c) Both of these.
    (d) Neither of these.
21. Colors in a soap bubble result from light
    (a) converted to a different frequency.
    (b) deflection.
    (c) subtracted from incident light.
    (d) amplification.
22. Polarization is a property of
    (a) transverse waves.
    (b) longitudinal waves.
    (c) all waves.
    (d) None of these.
23. A hologram best illustrates
    (a) polarization.
    (b) diffraction.
    (c) superposition.
    (d) electron interference.
24. In the proportion $E \sim f$, the f stands for the
    (a) frequency of light.
    (b) frequency of sound.
    (c) frequency of a tuning fork or vibrating string.
    (d) frictional force.
25. The energy of an emitted photon is related to its
    (a) amplitude.
    (b) polarization.
    (c) momentum.
    (d) frequency.
26. Among these colors, the one having the most energy per photon is
    (a) red.
    (b) yellow-green.
    (c) blue.
    (d) violet.
27. The red glow in the neon tube of an advertising sign is a result of
    (a) fluorescence.
    (b) incandescence.
    (c) excitation.
    (d) polarization.
28. All parts of a laser beam have the same
    (a) frequency.
    (b) phase.
    (c) speed.
    (d) All of these.
29. The model of light supported by the photoelectric effect is the
    (a) wave model.
    (b) particle model.
    (c) Both of these.
    (d) Neither of these.
30. Planck's constant can be found by dividing the energy of a photon by its
    (a) wavelength.
    (b) frequency.
    (c) amplitude.
    (d) None of these.

After you have made thoughtful choices, and discussed them with your friends, find the answers on page 681.