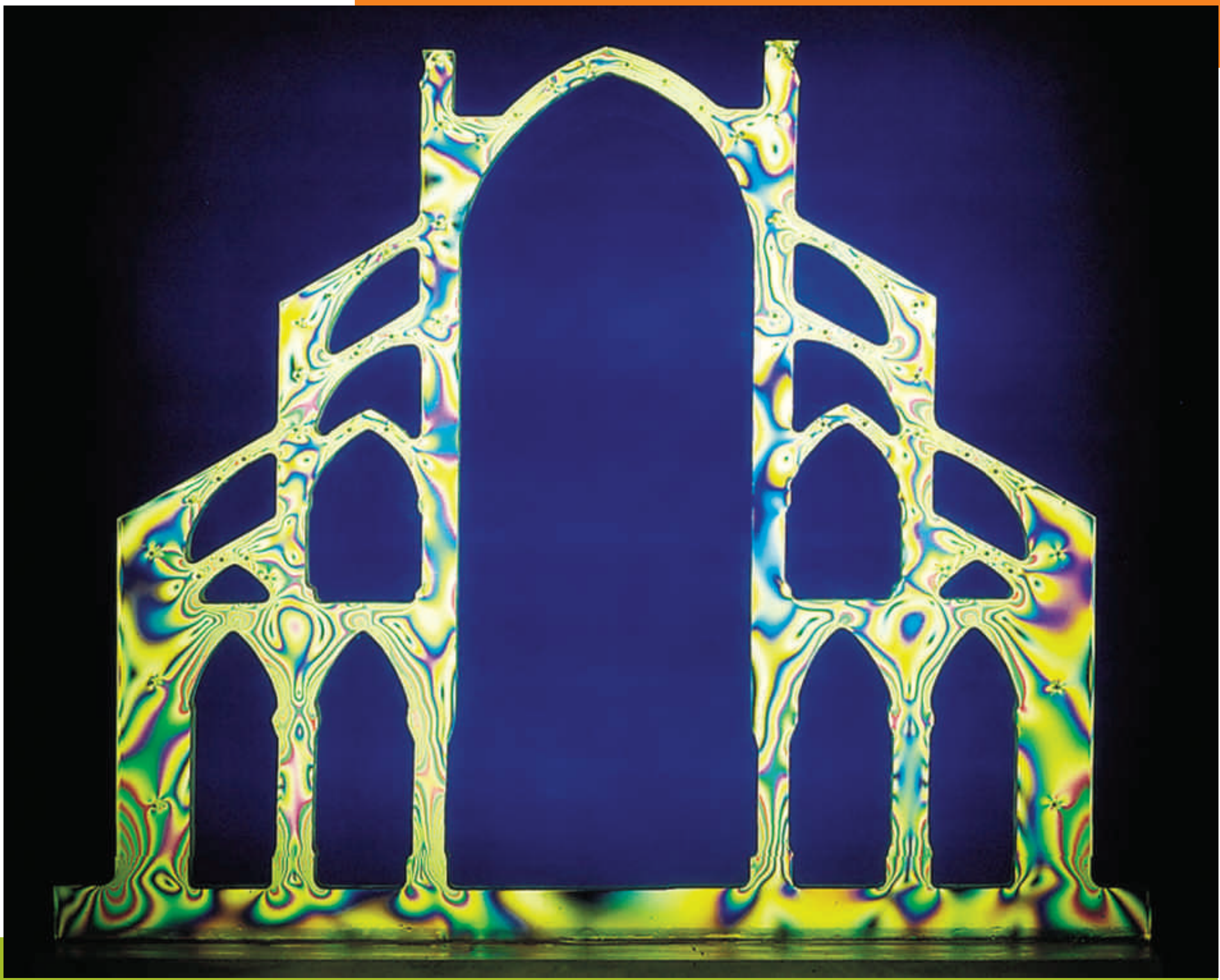
19

A Model for Light

▶Light is one of our most common everyday phenomena, and our knowledge of light is responsible for our understanding of the beautiful effects in soap bubbles and for technological advances into extending human perception. **But what is light?**

(See page 416 for the answer to this question.)



Robert Mark, Princeton University

Viewing a plastic model of a structure through crossed pieces of Polaroid filter shows the stress patterns in the structure. This photograph shows a model of the flying buttresses of the Notre Dame cathedral.

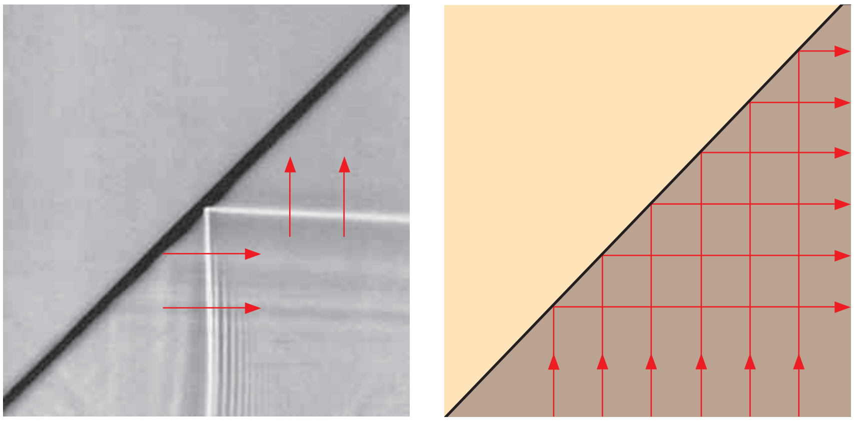
IN the previous two chapters, we learned a great deal about light by simply observing how it behaves, but we did not ask, "What is light?" This question is easy to ask, but the answer is more difficult to give. For example, we can't just say, "Let's look!" What we "see" is the stimulation caused by light entering our eyes, not light itself. To understand what light is, we need to look for analogies, to ask ourselves what things behave like light. In effect, we are building a model of a phenomenon that we can't observe directly. This same problem occurs quite often in physics because many components of nature are not directly observable. In the case of light, we need a model that accounts for the properties that we studied in the previous two chapters. When we look at the world around us, we see that there are two candidates: *particles* and *waves*.

So the question becomes, does light behave as if it were a stream of particles or a series of waves? Newton thought that light was a stream of particles, but other prominent scientists of his time thought that it behaved like waves. Because of Newton's great reputation, his particle model of light was the accepted theory during the 18th century. However, many of the early observations could be explained by a particle model *or* a wave model. Scientists continually looked for new observations that could distinguish between the two theories. We will examine the experimental evidence to see whether light behaves like particles or waves. The process of deciding is as important as the answer.

Reflection

We know from such common experiences as echoes and billiards that both waves and particles can bounce off barriers. But this fact is not enough. Our model for the behavior of light must agree with our conclusion that the angle of reflection is equal to the angle of incidence. A particle model for light can account for this if the reflecting surface is frictionless and perfectly elastic. A wave model of light also has no problem accounting for the law of reflection. The photograph in Figure 19-1(a) shows a straight wave pulse on the surface of water striking a smooth, straight barrier. The wave was initially moving toward the top of the picture and is being reflected toward the right. We see that the angle between the incident wave and the barrier is equal to that between the reflected wave and the barrier. In the corresponding ray diagram [Figure 19-1(b)], we draw the rays perpendicular to the straight wave fronts—that is, in the direction the wave is moving.

Observing that light reflects from surfaces gives us no clues as to its true nature; both particles and waves obey the law of reflection.



PSSC PHYSICS, 2nd edition, 1965, D.C. Heath & Co. and Education Development Center, Inc., Newton, MA.

(*a*) (*b*)

Figure 19-1 (a) The horizontal white line is a straight water-wave pulse moving toward the top of the picture. The part that has already hit the black barrier is reflected toward the right. (b) The corresponding ray diagram has rays perpendicular to the wave fronts and shows that the angle of reflection is equal to the angle of incidence.

▶ Extended presentation available in the *Problem Solving* supplement

Refraction

We learned a great deal in the previous chapter about the behavior of light when it passes through boundaries between different transparent materials. Newton thought that the particles of light experienced a force as they passed from air into a transparent material. This inferred force would occur only at the surface, act perpendicular to the surface, and be directed into the material. This force would cause the particles to bend toward the normal, as shown in Figure 19-2. In this scheme the light particles would also experience this force on leaving the material. Because the force acts into the material, it now has the effect of bending the particles away from the normal. Furthermore, when Newton calculated the dependence of the amount of **refraction** on the angle of incidence, his answer agreed with the curves in Figure 18-2. So the model gives not only the correct qualitative results but also the correct quantitative results.

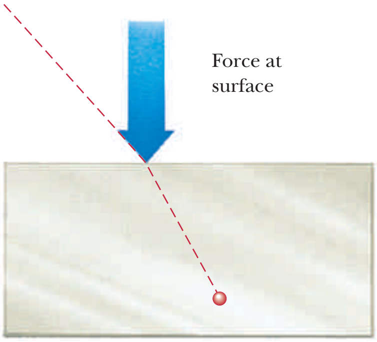


Figure 19-2 A force perpendicular to the surface would cause light particles to be refracted.

Water waves also refract. The photograph in Figure 19-3 shows the refraction of water waves. The boundary that runs diagonally across the photograph separates the shallow region on the left from the deeper region on the right. Once again, the numerical relationship between the angle of refraction and the angle of incidence is in agreement with the law of refraction.

There is an important difference between the wave and particle predictions; the speeds of the particles and waves do not change in the same way. Figures 19-2 and 19-3 both correspond to light entering a substance with a higher index of refraction. In the particle model, particles bend toward the normal because they speed up. Thus, the particle model predicts that the speed of light should be faster in substances with higher indexes of refraction.

In waves the opposite is true. Because the crests in Figure 19-3 are continuous across the boundary, we know that the frequency of the waves doesn't change. However, the wavelength does change; it is shorter in the shallow region to the left of the boundary. Because $v = \lambda f$ (Chapter 15), a decrease in the wavelength means a decrease in the speed of the wave. This means that the speed of the waves in the shallow region is smaller, and therefore the wave model predicts that the speed of light should be slower in substances with higher indexes of refraction.

Because the two models predict opposite results, we have a way of testing them; the speed of light can be measured in various materials to see which model agrees with the results. The speed of light in a material substance was not measured until 1862, almost two centuries after the development of the two theories. French physicist Jean Foucault measured the speed of light in

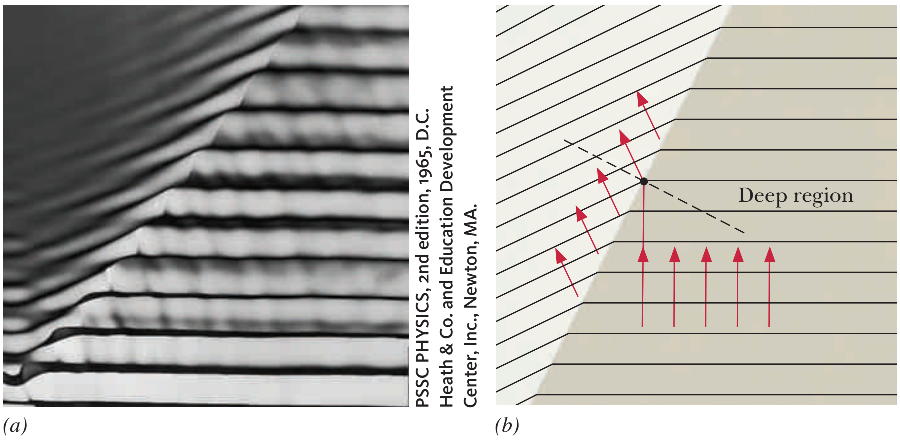


Figure 19-3 (a) Water waves refract when passing from deep to shallow water. (b) The corresponding ray diagram shows that the waves refract toward the normal.

air and water and found the speed in water to be less. This dealt a severe blow to the particle model of light and consequently caused a modification of the physics world view.

◀ light travels slower in materials

American physicist Albert Michelson improved on Foucault's measurements and found a ratio of 1.33 for the speed of light c in a vacuum to the speed of light v in water. This value is equal to the **index of refraction** n of water as predicted by the wave model, and thus $n = c/v$. Because the speed of light in a vacuum is the maximum speed, the indexes of refraction of substances must be greater than 1. This gives us a way of determining the speed of light in any material once we know its index of refraction. The speed of light in a substance is equal to its speed in a vacuum divided by the index of refraction, $v = c/n$.

◀ $n = c/v$

In the previous chapter, we discovered that different colors have slightly different indexes of refraction within a material, which results in **dispersion.** Because the index of refraction is related to the speed, we can now conclude that different colors must have different speeds in a material.

Q: Does red or blue light have the slower speed in glass?

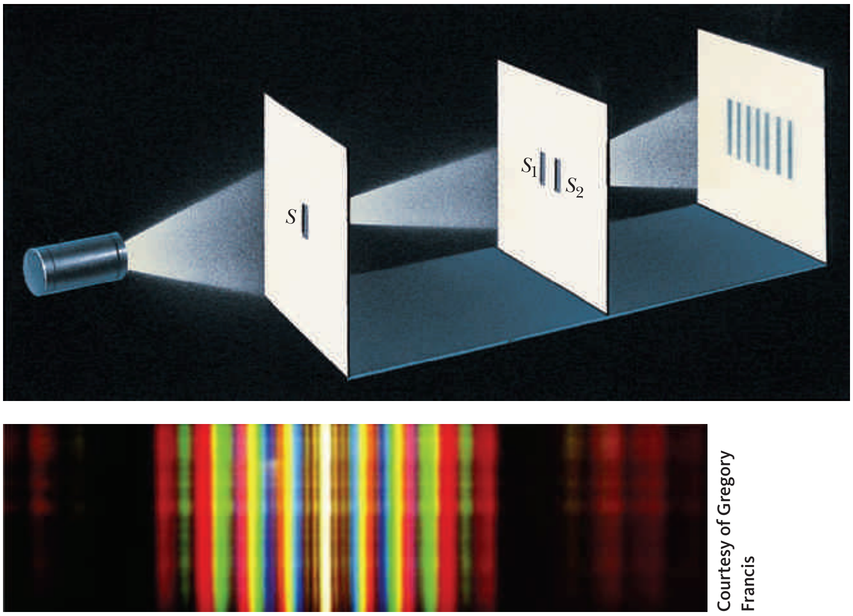
A: Because blue light is refracted more than red, it has the higher index of refraction. Therefore, blue light has a slower speed.

Interference

Although the speed of light in materials provided definitive support early on for the fact that light behaves like a wave, there was other supporting evidence in the debate. Newton's main adversary in this debate was largely unsuccessful at convincing others of the importance of the evidence. We now examine some of the other properties of waves that differ from those of particles and show that light exhibits these properties.

We begin with interference. The interference of two sources of water waves is shown in the photograph and drawing in Figure 15-20. Attempts to duplicate these results with two lightbulbs, however, fail. But if light is a wave phenomenon, it should exhibit such interference effects. Light from the two sources does superimpose to form an interference pattern, but the pattern isn't stationary. Stationary patterns are produced only when the two sources have the same wavelength and a constant phase difference; that is, when the time interval between the emission of a crest from one source and the emission of a crest from the second source does not change. Because the phase difference between the lightbulbs varies rapidly, the pattern blurs out, and the region looks uniformly illuminated.

The interference of two light sources was first successfully demonstrated by Thomas Young in 1801 (more than a half century before Foucault's work on the speed of light in materials), when he let light from *one* pinhole impinge on two other pinholes [Figure 19-4(a)]. Passing the light through the first pinhole produced light at the second pinholes that was reasonably in phase. The pattern shown in Figure 19-4(b) consists of colored bars formed by light from the two slits interfering to form antinodal regions. These antinodal regions have large amplitudes and appear bright. Each color forms its own set of colored bars. Antinodal regions for the different rainbow colors superimpose to produce the colors we perceive. Modern versions of this experiment are in complete agreement with the wave model.



(a)

(b)

Courtesy of Gregory Francis

Figure 19-4 (a) A schematic of Young's experiment that demonstrated the interference of light. (b) The interference pattern produced by white light incident on two slits.

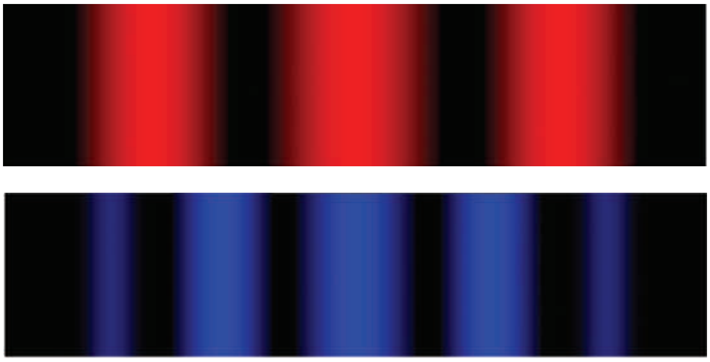
If the slits are illuminated with a single color, the pattern looks much like the one you would expect to find along the far edge of the ripple tank in Figure 15-20. As the color of the light changes, the pattern on the screen changes size (Figure 19-5). Red light produces the widest pattern, and violet light produces the narrowest one. The sizes produced by other colors vary in the same order as the colors of the rainbow.

Are You On the Bus?

Q: What happens to the width of one of these interference patterns if the distance between the two slits is increased?

A: We learned in Chapter 15 that the spacing of the nodal lines depends on the ratio of the wavelength to the slit separation. Therefore, the wider spacing will produce a narrower pattern.

Recall that in looking at the two-source interference patterns in Chapter 15, the nodal lines on each side of the central line were created by a difference in the path lengths from the two sources that was equal to one-half wavelength (Figure 15-21). Increasing the wavelength causes these nodal lines to move farther away from the central line; the pattern widens. Therefore, the shifting of the dark regions on our screen with color can be explained by a change in



(a)

(b)

Courtesy of Gregory Francis (both)

Figure 19-5 The two-slit interference pattern produced by red light (a) is wider than that produced by blue light (b).

wavelength. We conclude that the color of light depends on its wavelength, with red being the longest and violet the shortest.

Measurements of the interference pattern and the separation of the slits can be used to calculate the wavelength of the light. Experiments show that visible light ranges in wavelength from 400 to 750 nanometers (nm), where a nanometer is 10^{-9} meter. It takes more than 1 million wavelengths of visible light to equal 1 meter. Knowing the speed of light to be 3.0×10^8 meters per second, we can use the relationship $c = \lambda f$ to calculate the corresponding frequency range to be roughly $(4.0 \text{ to } 7.5) \times 10^{14}$ hertz.

Figure 19-6 A device for viewing two-slit interference.

You can perform Young's two-slit experiment by taping the slits to one end of the cardboard tube from a roll of paper towels. To make the two slits, blacken a microscope slide (or other piece of glass) with a candle flame. Scratch two viewing slits on the blackened side by holding two razor blades tightly together and drawing them across the slide. Cut a slit about 2 millimeters wide in a piece of paper and tape it to the other end of the tube. Aim this end of the tube at a light source and look through the end with the two slits to see the interference pattern (Figure 19-6).

You can vary the wavelength of the light by using pieces of red and blue cellophane as filters. Putting a thin spacer between the razor blades will vary the spacing.

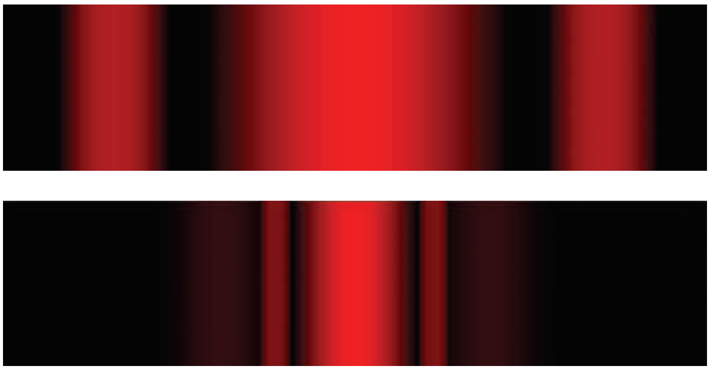
Diffraction

Young's experiment points out another aspect of waves. His interference pattern was possible only because light from one pinhole overlapped that from the other. Light spreads out as it passes through the pinholes. In other words, light exhibits diffraction just like the water waves of Figure 15-23.

The photographs in Figure 19-7 were taken of the diffraction pattern produced by light passing through a narrow slit. The slit was wider in Figure 19-7(b)! But this difference in the patterns makes sense if you examine the photographs of water waves in Figure 15-23. Contrary to what common sense may tell us, the narrower slit produces the wider pattern. These patterns are in agreement with the wave model and contrary to what we would expect if light traveled only in straight lines. In the case of particles, the wider slit would produce the wider pattern, not the narrower one.

Q: Does red light or blue light produce the wider diffraction pattern?

A: The width of the diffraction pattern depends on the ratio of the wavelength to the width of the slit. Because red light has the longer wavelength, it would produce the wider pattern.



Courtesy of Gregory Francis (both)

(a)

(b)

Figure 19-7 Diffraction patterns produced by red light incident on (a) a narrower and (b) a wider slit. The narrower slit produced the wider pattern.

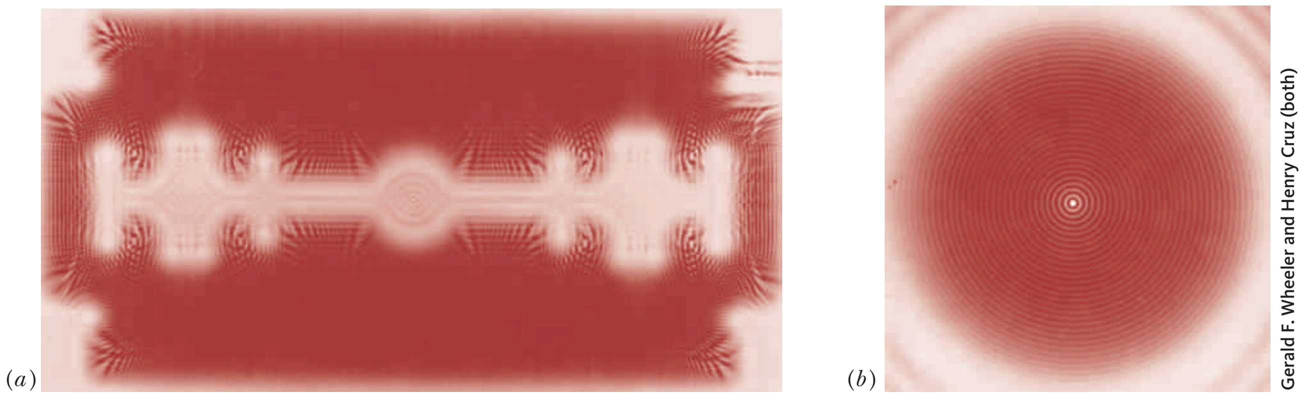


Figure 19-8 Photographs of diffraction patterns in the shadows of (a) a razor blade and (b) a penny.

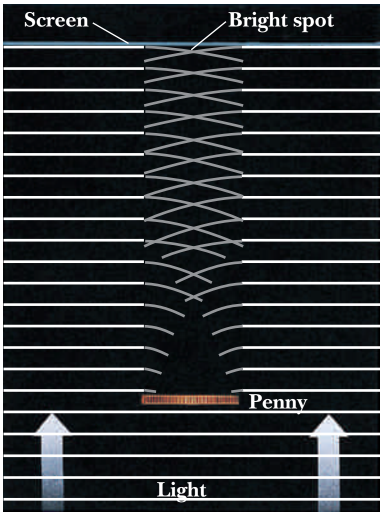


Figure 19-9 Diagram illustrating how wave interference and diffraction produce a bright spot at the center of the penny's shadow.

Water waves also show that diffraction takes place around the edges of barriers. To observe this effect with light, we should look along the edge of the shadow of an object. This effect is usually not observed with light because most shadows are produced by broad sources of light. The resulting shadows have smooth changes from umbra through penumbra to full brightness. Therefore, we should look at shadows produced by point sources to eliminate the penumbra.

The photographs in Figure 19-8 were created by putting photographic paper in the shadows of a razor blade and a penny. We used red light from a laser because the light waves are in phase and can easily be made to approximate a point source. You can see that the edges of the shadows show the effects of the interference of diffracted light. Only a wave model of light can explain these effects.

Notice the center of the shadow of the penny. Even though the penny is solid, the shadow has a bright spot in the center. Can the wave model explain this bright spot? The diagram in Figure 19-9 shows how the light diffracts around the edge of the penny. The light coming from each point on the edge travels the same distance to the center of the shadow. These waves arrive in phase and superimpose to form the bright spot. This is added support for the wave model of light.

It is possible to observe the diffraction of light in everyday situations. Look at a lightbulb through the slit between two fingers held in front of your eyes, as in Figure 19-10. How does the image of the lightbulb change as you slowly change the spacing between your fingers? Notice the dark, vertical lines in the image. What happens to those lines as your fingers move closer together?

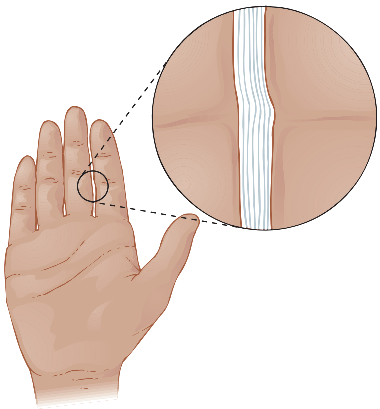


Figure 19-10 Light viewed through the thin slit between two fingers exhibits diffraction effects.

Thin Films

Soap bubbles, oil slicks, and thin films of any transparent material exhibit beautiful arrays of color under certain conditions—an effect not of dispersion but of interference.

Consider a narrow beam of red light incident on a thin film, as shown in Figure 19-11. At the first surface, part of the light is reflected and part is transmitted. The same thing happens to the transmitted part when it attempts to exit the film; part is transmitted and part is reflected, and so on. Considering just the first two rays that leave the film on the incident side, we can see that

Everyday Physics | *Diffraction Limits*

The wave nature of light and the size of the viewing instrument limit how small an object we can see, even with the best instruments. Because of the wave nature of light, there is always some diffraction. The image is spread out over a region in space; the region is larger for longer wavelengths and smaller openings.

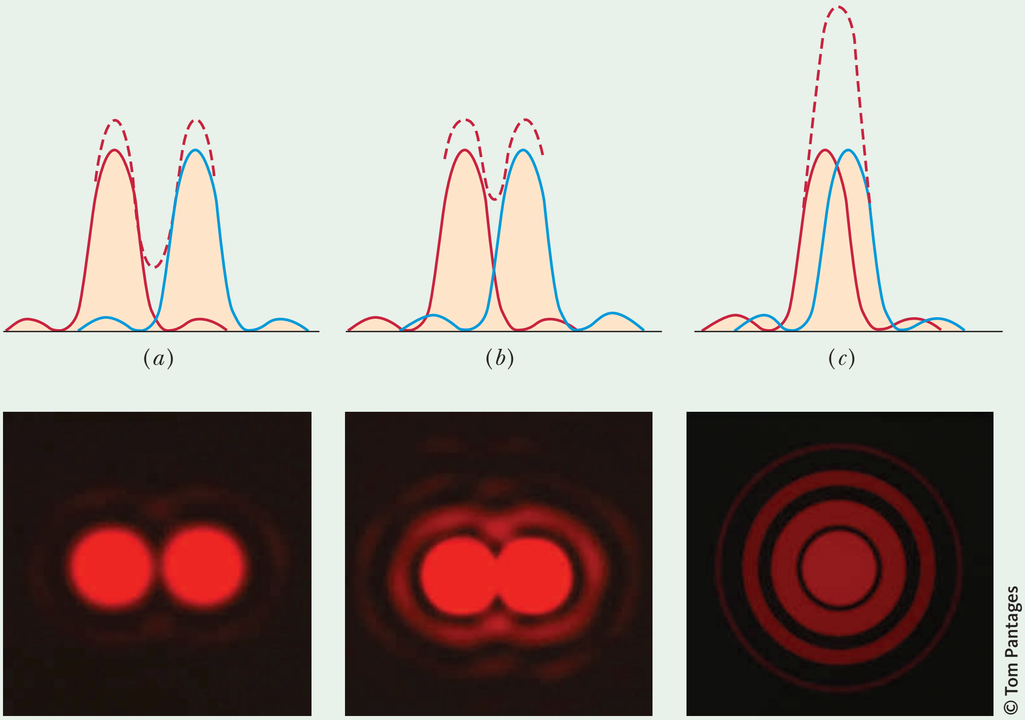
Consider two objects with small *angular* sizes (they could be very big but so far away that they look small) separated by a small angular distance. Each of these will produce a diffraction pattern when its light passes through a small opening such as in our eye or a telescope. The diagram and photograph in (a) correspond to the case in which the diffraction patterns can still be clearly distinguished. In (c) the overlap is so extensive that you cannot resolve the individual images. The limiting case is shown in (b); the separation of the centers of the two patterns is less than the width of the central maximum of either pattern. At this limit the first minimum of each pattern lies on top of the maximum of the other pattern.

This minimum angular separation can be calculated mathematically. The light coming from two point sources can be resolved if the angle (measured in radians) between the objects is greater than 1.22 times the ratio of the wavelength of the light to the diameter of the aperture. Imagine viewing an object from a distance of 25 centimeters, the nominal distance of closest vision. If we use an average pupil size of 5 millimeters and visible light with a wavelength of 500 nanometers, we calculate that you can distinguish a separation of 0.03 millimeter, about the radius of a human hair. A similar calculation tells us that we should be able to distinguish the headlights of an oncoming car at a distance of 10 kilometers.

From this relationship you can see why astronomers want bigger telescopes. With a larger mirror, the resolving angle is smaller, and they can distinguish more detail in distant star clusters. For instance, the resolving angle of a 5-meter telescope in visible light is about 0.02 arc second, where 1 arc second is $\frac{1}{3600}$ degree. In practice, this resolution is never obtained because turbulence in Earth's atmosphere limits the resolution to about 1 arc second. This is one of the major reasons for placing the Hubble Space Telescope in orbit.

Diffraction effects also place lower limits on the sizes of objects that can be examined under an optical microscope because the details to be observed must be separated by more than the diffraction limits set by the microscope.

1. Is it better to use red light or blue light to minimize diffraction effects while photographing tiny objects through a microscope? Why?
2. Why are the diffraction effects of your eyes more important during the day than at night?



Two overlapping diffraction patterns can just barely be resolved (b) if the central maximum of each pattern lies on the first minimum of the other. If the patterns are closer, they appear to be a single object (c).

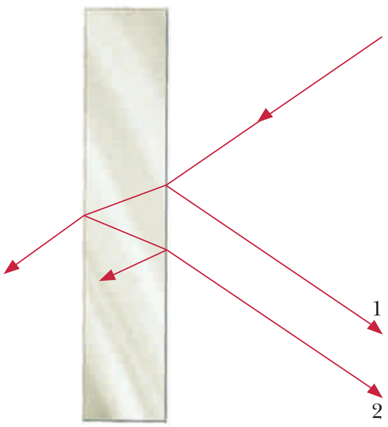


Figure 19-11 Light incident on a thin film is reflected and transmitted at each surface. Rays 1 and 2 interfere to produce more or less light, depending on the thickness of the film and the wavelength of the light in the film.

they interfere with each other. Because of the thickness of the film, ray 2 lags behind ray 1 when they overlap on the incident side of the film. Ray 2 had to travel the extra distance within the film. At a certain thickness, this path difference is such that the crests of one ray line up with the troughs from the other and the two rays cancel. In this case little or no light is reflected. At other thicknesses, the crests of one ray line up with the crests from the other, and the two rays reinforce. In this case light is reflected from the surface.

Because different colors have different wavelengths, a thickness that cancels one color may not be the thickness that cancels another. If the film is held vertically (Figure 19-12), the pull of gravity causes the film to vary in thickness, being very thin at the top and increasing toward the bottom. In fact, when the film breaks, it begins at the top where it has been stretched too thin. If the film varies in thickness and the incident light is white, different colors will be reflected for different thicknesses, producing the many colors observed in soap films.

Notice that the very thin region at the top of the soap film in Figure 19-12 has no light reflecting from the film. At first this seems confusing. Because there is essentially no path difference between the front and back surfaces, we may expect light to be reflected. However, the first ray is inverted when it reflects; that is, crests are turned into troughs, and vice versa. This process is analogous to the inversion that takes place when a wave pulse is reflected from the fixed end of a rope (Chapter 15). Light waves are inverted when they reflect from a material with a higher index of refraction. At the back surface, the rays reflect from air (a lower index of refraction than the soap), and no inversion takes place.

Q: Why does part of the thin film in Figure 19-12 appear white when white is not one of the rainbow colors?

A: We observe white when most of the colors overlap.

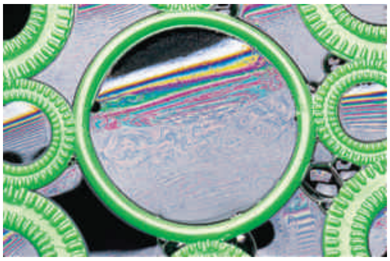


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Figure 19-12 Different colors are reflected from different thicknesses of the thin film. The very thin region at the top of the soap film appears black because the reflected light is inverted at the front surface but not at the back surface.

Because the ray reflected from the front surface is inverted while the ray reflected from the back surface is not inverted, a crest from the front surface will overlap a trough from the back surface if the thickness of the film is much smaller than a wavelength. The two reflected rays will cancel, and no light will be reflected. If the light is normal to the surface and the thickness of the film is increased until it is one-quarter of a wavelength thick, the light will now be strongly reflected. The ray that reflects from the back surface must travel an extra one-half wavelength, and these crests and troughs will be delayed so that they now line up with those reflected from the front surface. It is important to note that we are referring to the wavelength of the light *in the film*. Because the frequency of the light is the same in the air and in the film while the speed is reduced, the wavelength in the film is equal to that in the air divided by the index of refraction, $\lambda_f = \lambda/n$.

This colorful phenomenon also occurs after rain has wetted the highways. Oil dropped by cars and trucks floats on top of the puddles. Sunlight reflecting from the top surface of the oil and from the oil–water interface interferes to produce the colors. Again, variations in the thickness of the oil slick produce the array of colors.

Interference also occurs for the transmitted light. Light passing directly through the thin film (Figure 19-13) can interfere constructively or destructively with light that is reflected twice within the film. The effects are complementary to those of the reflected light. When the thickness of the film is chosen to minimize the reflection of a certain color of light, the transmission

WORKING IT OUT Thin Film

You are coating a glass lens of index of refraction 1.5 with a film of material of index of refraction 1.6. You start with the thinnest film possible that creates a strong reflection for 600-nm (orange) light. You gradually increase the film thickness until you again get strong reflection. What is the thickness of the film now? How would your answer change if the glass lens had an index of refraction of 1.7?

The light rays are inverted when they reflect at the front surface of the film (going from index of refraction of 1.0 in air to 1.6 in the film). The rays are not inverted at the back surface of the film (going from index of refraction of 1.6 in the film to 1.5 in the glass). The thinnest possible film that will yield strong reflection is therefore $\lambda/4$, where λ is the wavelength of the light in the film. The next strong reflection will occur when the extra path length in the film is one whole wavelength. This means increasing the thickness of the film by half a wavelength:

$$t = \frac{\lambda}{4} + \frac{\lambda}{2} = \frac{3\lambda}{4} = \frac{3\lambda_{air}}{4n} = \frac{3(600 \text{ nm})}{4(1.6)} = 281 \text{ nm}$$

If the glass lens instead has an index of refraction of 1.7, greater than that of the film, then the light rays will invert at both surfaces. The first strong reflection will now occur when the film is half a wavelength thick. The next strong reflection will again occur when the path length in the film is increased by one whole wavelength. This means increasing the thickness of the film by half a wavelength:

$$t = \frac{\lambda}{2} + \frac{\lambda}{2} = \lambda = \frac{\lambda_{air}}{n} = \frac{600 \text{ nm}}{1.6} = 375 \text{ nm}$$

FLAWED REASONING

A factory worker is coating camera lenses with a special film to filter out red light by reflecting the red light from the surface. The index of refraction of the film is greater than that of the lens. The boss has instructed him to make the film 110 nanometers thick. The worker decides that "more is always better" and that the boss should not be so stingy with the coating material. He therefore makes the coating twice as thick. **Will the customers get a better red filter than they bargained for?**

ANSWER The boss is not being stingy. The coating filters red light if its thickness is one-quarter the wavelength of the red light in the material. This causes the light that reflects from the back of the coating to be in phase (crest lined up with crest) with the light that reflects from the front of the coating. If the thickness of the coating is doubled, these two reflections will be out of phase, and the red light will pass through the lens instead of being reflected.

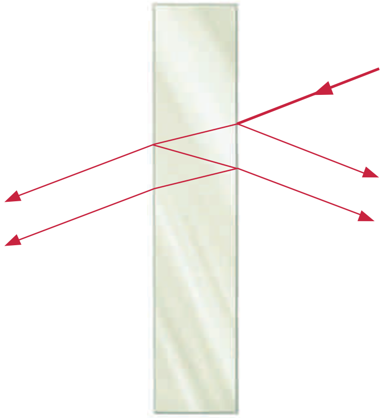

Figure 19-13 The light transmitted through a thin film also displays interference effects.

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The colors on the puddle are caused by the interference of light reflected from the top and bottom of a thin oil film floating on the surface.

of that color is maximized. This process is a consequence of the conservation of energy. The light must go someplace.

Some modern office buildings have windows with thin films to reduce the amount of light entering the offices. The visors in the helmets of space suits are coated with a thin film to protect the eyes of the astronauts. Thin films are also important to lens makers because the proper choice of material and thickness allows them to coat lenses so that they do not reflect certain colors or conversely so that they do not transmit certain colors. It is common


NASA

The thin film on the visor protects the astronaut's eyes.

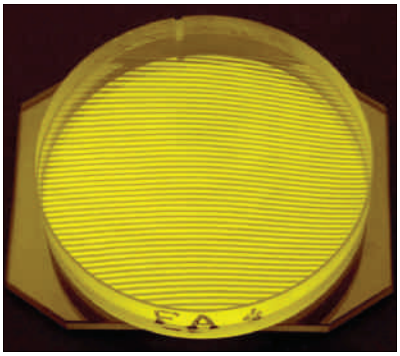
to coat the lenses in eyeglasses with a thin film to stop the transmission of ultraviolet light. Lenses in high-quality telescopes and binoculars are coated to reduce the reflection (and therefore enhance the transmission) of visible light, increasing the brightness of images.

An interesting example of thin-film interference was observed by Newton (even though he did not realize that it supported the wave model of light). When a curved piece of glass such as a watch glass is placed in contact with a flat piece of glass, a thin film of air is formed between the two. An interference pattern is produced when the light reflects from the top and bottom of the air gap. The interference pattern that is formed by a wedge-shaped air gap is shown in Figure 19-14. Such patterns are commonly used to test the surface quality of lenses and mirrors.

Q: Would you expect to find a dark spot or a bright spot when you look at the reflected light from an air gap of almost zero thickness?

A: The light waves will be inverted when they reflect off the second interface, but not the first one. Therefore, you would see a dark spot in the reflected light and a bright spot in the transmitted light.

Figure 19-14 (a) Interference lines are produced by light reflecting from the top and bottom surfaces of an air wedge between two pieces of glass.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(a)

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Polarization

We have established that light is a wave phenomenon, but we have not discussed whether it is transverse or longitudinal—that is, whether the vibrations take place perpendicular to the direction of travel or along it. We will determine this by examining a property of transverse waves that does not exist for longitudinal waves and then see whether light exhibits this behavior.

Transverse waves traveling along a horizontal rope can be generated so that the rope vibrates in the vertical direction, the horizontal direction, or any direction in between. If the vibrations are in only one direction, the wave is said to be *plane polarized,* or often just **polarized.** This property becomes important when a wave enters a medium in which various directions of polarization are not treated the same. For instance, if our rope passes through a board with a vertical slit cut in it (Figure 19-15), the wave passes through the slit if the vibration is vertical but not if it is horizontal.

What happens if the slit is vertical but the polarization of the wave is someplace between vertical and horizontal? Imagine that you are looking along the length of the rope, and we represent the polarization of the wave by an arrow (a vector) along the direction of vibration. This polarization can be

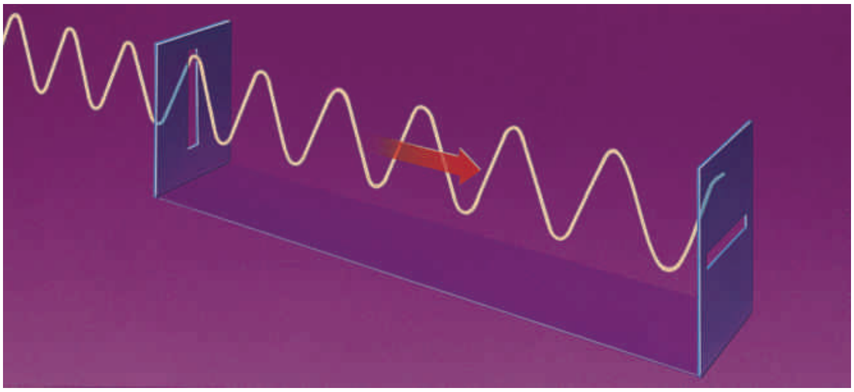

Figure 19-15 Waves with vertical polarization pass through a vertical slit, but not through a horizontal one.

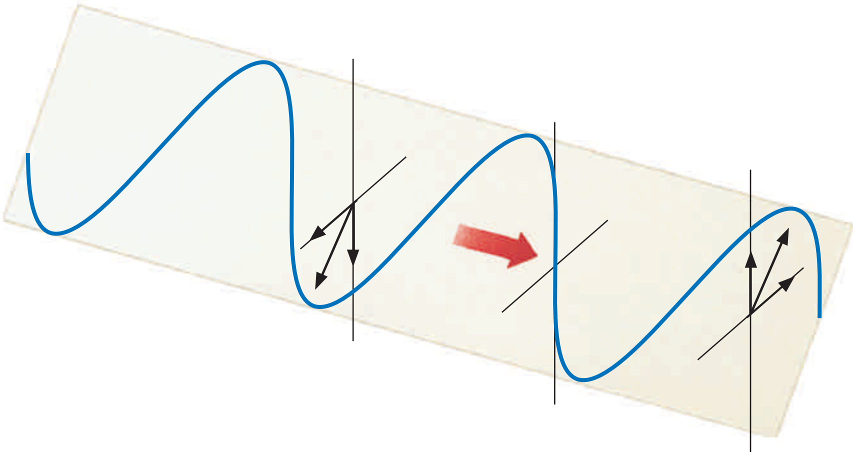

Figure 19-16 The plane-polarized wave can be broken up into two perpendicular component waves: one in the vertical plane and one in the horizontal plane. The displacements of these component waves are shown at two sample locations.

imagined as a superposition of a vertical vibration and a horizontal vibration, as illustrated in Figure 19-16. The vertical slit allows the vertical vibration to pass through while blocking the horizontal vibration. Therefore, the wave has a vertical polarization after it passes through the vertical slit. The amplitude of the transmitted wave is equal to the amplitude of the vertical vibration of the incident wave.

Determining whether light can be polarized is a little difficult because our eyes cannot tell whether light is polarized. Nature, however, provides us with materials that polarize light. The mere existence of polarized light demonstrates that light is a transverse wave. If it were longitudinal, it could not be polarized. Commercially available light-polarizing materials, such as Polaroid filters, consist of long, complex molecules whose long axes are parallel. These molecules pass light waves with polarizations perpendicular to their long axes but absorb those parallel to it.

◀ light is a transverse wave

We can use a piece of Polaroid filter (or the lens from Polaroid sunglasses) to analyze various light sources to see whether they are polarized. If the light is polarized, the intensity of the transmitted light will vary as the Polaroid filter is rotated. This simple procedure shows that common light sources such as ordinary incandescent lamps, fluorescent lights, candles, and campfires are unpolarized. However, if we examine the light reflected from the surface of a lake, we find that it is partially polarized in the horizontal direction. Light reflected from nonmetallic surfaces is often partially polarized in the direction parallel to the surface. This is the reason why the axes of polarization of Polaroid sunglasses are in the vertical direction. Boaters know that Polaroid sunglasses remove the glare from the surface of water and allow them to see below the surface.

Photographs taken through a plate-glass window (a) with and (b) without a polarizing filter on the camera lens. Notice that the polarizing filter eliminates the glare.

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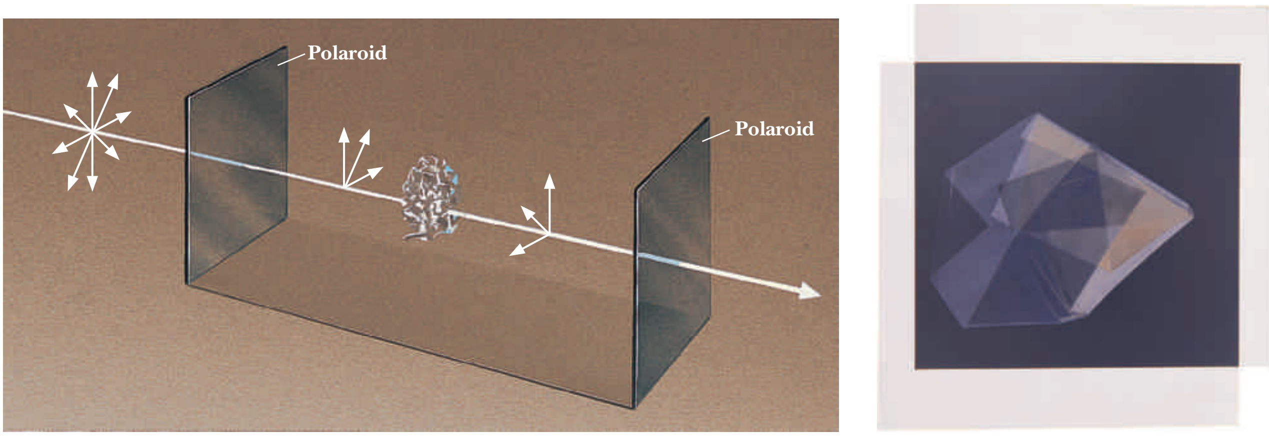
(a) (b)

Until now we have discussed materials in which one direction passes the light and the other absorbs it. Some materials allow both polarizations to pass through, but the orientations have different speeds. This can have the effect of rotating the plane of polarization. The cellophane on cigarette packages and some types of transparent adhesive tape have this property.

You can make an interesting display by crumpling a cigarette wrapper and looking at it between two Polaroid filters, as in Figure 19-17(a). The Polaroid filter on the side near the light polarizes the light striking the display. When this light is viewed with the second Polaroid filter, the different thicknesses of cellophane have different colors, as shown in Figure 19-17(b). The amount of rotation depends on the thickness of the cellophane and the wavelength of the light. Certain thicknesses rotate certain colors by just the right amount to pass through the second Polaroid filter. Others are partially or completely blocked. The colors of each section change as either Polaroid filter is rotated.



Charles D. Winters

(a) (b)

Figure 19-17 (a) Cellophane or transparent tape rotates the plane of polarization. (b) A pattern formed by different thicknesses of cellophane viewed between two pieces of Polaroid filter.

Glasses and plastics under stress rotate the plane of polarization, and the greater the stress the more the rotation. Plastic models of structures, such as cathedrals, bones, or machined parts, can be analyzed to discover where the stress is greatest.

Looking Ahead

We have not finished our quest to understand light. Notice, for example, that although we established that the wave model of light explains all the phenomena we have observed so far, we still have not said what it is that is waving! We know that light travels from the stars to our eyes through incredible distances in a vacuum that is much better than any we can produce on Earth. How is this possible?

We will see in Chapter 23 that understanding the nature of light was the key to our modern understanding of atoms. This reexamination of the model for light occurred at the beginning of the 20th century and began with Einstein asking many of the same questions that we addressed here.

Summary

Developing a theory of light involves building a model from known experiences that can be compared with the behavior of light. Both particle and wave models can account for the law of reflection and the law of refraction. However, only a wave model can correctly account for the speed of light in transparent materials. The index of refraction n is the ratio of the speed of light c in a vacuum (300 million meters per second) to its speed v in the material; that is, $n = c/v$. Dispersion of light indicates that different colors have different speeds in a material.

Other properties of waves that differ from those of particles further support the fact that light is a wave phenomenon. Interference of two coherent light sources produces a stationary pattern. If different colors are used, the pattern changes size, demonstrating that colors have different wavelengths. Red light has the largest wavelength and produces the widest pattern, and violet light produces the narrowest one. Visible light ranges in wavelength from 400 to 750 nanometers.

Light exhibits diffraction, which is the spreading out of a wave as it passes through narrow openings and around the edges of objects. The width of the diffraction pattern depends on the ratio of the wavelength to the size of the opening—the narrower the opening, the wider the pattern. Because red light has the longest visible wavelength, it produces the widest pattern for a given opening.

Thin films of transparent materials exhibit beautiful arrays of colors due to the interference of light rays reflecting from the two surfaces. A ray that reflects from a material with a higher index of refraction is inverted. Different wavelengths are strongly reflected or transmitted at different thicknesses of film.

Light exhibits polarization, demonstrating that it is a transverse wave. Polarizing materials pass light waves with polarizations perpendicular to one axis, but absorb those parallel to it. Common light sources are usually unpolarized. However, light reflected from the surface of a lake or glass is partially polarized parallel to the surface.

Everyday Physics | *Holography*

Wouldn't it be fantastic to have a method for catching waves, preserving the information they carry, and then at some later time playing them back? In fact, high-fidelity equipment routinely records a concert and plays it back so well that the listeners can hardly tell the difference. Similarly, high-fidelity photography should record the light waves coming from a scene and then play them back so well that the image is nearly indistinguishable from the original scene.

Conventional photography, however, does not do this. Although modern chemicals and papers have created images with extremely fine resolution, nobody is likely to mistake a photograph for the real object because a photographic image is two-dimensional, whereas the scene is three-dimensional. This loss of depth means that you can view the scene in the photograph from only one angle, or perspective. You cannot look around objects in the foreground to see objects in the background. The objects in the scene do not move relative to one another as you move your point of view.

Holography is a photographic method that produces a three-dimensional image that has virtually all the optical properties of the scene. This process was conceived by Dennis Gabor in 1947; he received a Nobel Prize in 1971 for this work. Gabor chose the word *hologram* to describe the three-dimensionality of the image by combining the Greek roots *holo* ("complete") and *gram* ("message").

Although Gabor could make a hologram out of a flat transparency, the lack of a proper light source prevented him from making one of an object with depth. With the invention of the laser in 1960, interest in holography was renewed. We will postpone the discussion of laser operation until Chapter 24. At the moment we need only know that it is a device that produces light with a single color and a constant phase relationship.

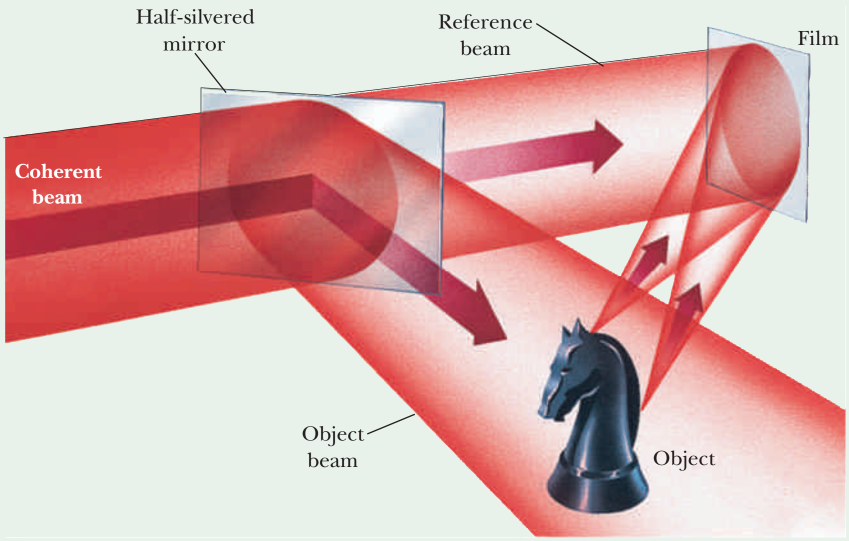
Figure A shows the essential features of a setup for making holograms. Notice that there is no lens between the object and the film. Light from the object reflects onto all portions of the film. Although this *object beam* carries the information about the object, if this were all that happened, the film would be completely exposed, and virtually no information about the object would be recorded.

Another portion of the beam from the laser (the *reference beam*) illuminates the film directly. Once again, if this were all that happened, the film would not record the scene. However, the light from the laser has a single well-defined wavelength (color) with the crests lined up. Therefore, the light reflected from the object and the light in the reference beam produce an interference pattern that is recorded in the film. This interference pattern contains the three-dimensional information about the scene.

The hologram is viewed by placing it back in a reference beam. The pattern in the film causes the light passing through it to be deflected so that it appears to come from the original scene (Figure B).

Because information from each point in the scene is recorded in all points of the hologram, a hologram contains information from

Figure A Making a hologram.



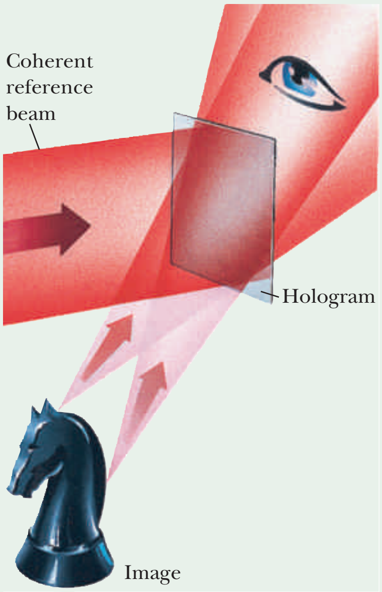


Figure B A hologram is viewed by placing it in the reference beam. The light passing through the film produces a virtual image at the location of the original scene.

all perspectives covered by the film. Therefore, viewing a hologram is just like viewing the original scene through a window. The photographs in Figure C were taken of a single hologram. Note that the relative locations of the chessmen change as the camera position changes. This is what we would see if we were looking at the actual chessboard.

Because information from each point in the scene is recorded in all points of the hologram, a hologram can be broken, and each piece will produce an image of the entire scene. Of course, something must be lost. Each piece will allow the scene to be viewed only from the perspective of that piece. This is analogous to looking at a scene through a window that has been covered except for a small hole.

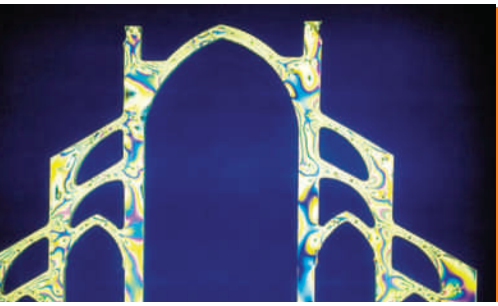
Advances in holography have made it possible to display holograms with ordinary sources of white light instead of the much more expensive lasers. It is now possible to hang holograms in your home as you would paintings. In fact, they have become so inexpensive that they have appeared on magazine covers. Holograms can also be made in the shape of cylinders so that you can walk around the hologram and see all sides of the scene. In some of these, individuals in the scene move as you walk around the hologram. Holographic movies are possible, and holographic television should be possible in the future.

In addition to being a fantastic art medium, holography has found many practical applications. It can be used to measure the three-dimensional wear patterns on the cylinder walls of an engine to an accuracy of a few ten-thousandths of a millimeter (a hundred-thousandth of an inch), perform nondestructive tests of the integrity of machined parts or automobile tires, study the shape and size of snowflakes while they are still in the air, store vast quantities of information for later retrieval, and produce three-dimensional topographical maps.

1. What characteristics of laser light are critical to the creation of a holographic image?
2. A piece of film containing a hologram is cut into four equal parts. How will the hologram observed in one of these parts compare to the original hologram?

Figure C The relative positions of the chessmen in the holographic image change as the point of view changes.

Gerald F. Wheeler (both)



CHAPTER 19 *Revisited*

Light is probably the most fascinating and elusive phenomenon in nature. The answer to the question, "What is light?" changes with the techniques used to examine the question. In this chapter we found good evidence to support the conclusion that light is a wave phenomenon. In future chapters we'll return to this question and delve further into the mystery of light.

Key Terms

dispersion The spreading of light into a spectrum of colors. The variation in the speed of a periodic wave due to its wavelength or frequency.

index of refraction An optical property of a substance that determines how much light bends on entering or leaving it. The index is equal to the ratio of the speed of light in a vacuum to its speed in the substance.

polarized A property of a transverse wave when its vibrations are all in a single plane.

refraction The bending of light that occurs at the interface between two transparent media. It occurs when the speed of light changes.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. Newton believed that light beams consist of tiny particles. If these beams travel in straight lines, what does that imply about their speed?
2. How does the particle theory of light account for the diffuse reflection of light?
3. Argue that the law of reflection would not hold for particles rebounding from a surface that is not frictionless or not perfectly elastic.
4. When a particle reflects elastically from a smooth surface, the component of the particle's momentum parallel to the surface is conserved while the component of the particle's momentum perpendicular to the surface is reversed. Use this information to argue that Newton's particle theory of light is consistent with the observation that the angle of incidence equals the angle of reflection.
5. If particles incident at 45 degrees from the normal strike a completely elastic surface that has friction, will the angle of reflection (with respect to the normal) be greater than, equal to, or less than 45 degrees? Explain.
6. If particles incident at 45 degrees from the normal strike a frictionless surface that is not completely elastic, will the angle of reflection (with respect to the normal) be greater than, equal to, or less than 45 degrees? Explain.
7. How does Newton's idea of light particles explain the law of refraction?
8. Explain how Newton's idea of light particles predicts that the speed of light in a transparent material will be faster than in a vacuum.
9. Does the wave's frequency or its wavelength remain the same when the wave crosses from one medium into another? Explain.
10. In which region of Figure 19-3(a) (top left or bottom right) are the waves traveling at the higher speed? Explain.
11. Which color of light, red or blue, travels faster in a diamond? Explain your reasoning.
12. Do you expect the speed of light in glass to be slower than, faster than, or the same as that in diamond? Why?
13. What property of a light wave determines its brightness?
14. Does the amplitude of a light wave increase, decrease, or stay the same on reflection from a transparent material? Explain.
15. Starting with the observation that waves that have been bent toward the normal have a shorter wavelength than the incident waves, explain how the wave model for light

predicts that the speed of light in glass will be slower than the speed in a vacuum.

16. Imagine that Newton knew that light travels slower in glass than in air but was unaware of the law of refraction. In what direction would he have predicted light to bend when passing from air into glass?

17. Does total internal reflection result from light trying to pass from a slow medium to a fast medium or from a fast medium to a slow medium? Explain.

18. Different colors of light have different critical angles for total internal reflection. Is the critical angle greater for colors of light that travel faster or slower in the medium? Explain.

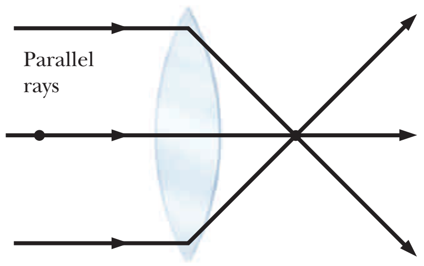
19. What is the physical difference between red and blue light?

20. How does the slow speed of light in diamonds affect their brilliance?

21. Why do we not notice any dispersion when white light passes through a windowpane?

22. What does the dispersion of light tell us about the speeds of various colors of light in a material?

23. Will the converging lens in the following figure focus blue light or red light at a closer distance to the lens? Explain.



Questions 23 and 24.

24. Using blue light, you determine the focal point for the lens in the preceding figure. If you were to shine a green laser beam from this focal point to a point near the top of the lens, would the emerging beam be bent toward or away from the optic axis? Explain.

25. Red light is used to form a two-slit interference pattern on a screen. As the two slits are moved farther apart, does the separation of the bright bands on the screen decrease, increase, or remain the same? Why?

26. What happens to the separation of the bright bands in a two-slit interference pattern if the slits are made narrower but their separation remains the same?

27. Would yellow light or green light produce the wider two-slit interference pattern? Why?

28. We observe that the two-slit interference pattern produced by blue light is narrower than that produced by red light. What does this tell us about red and blue light?

29. What determines whether two light beams with the same wavelength tend to cancel or reinforce each other?

30. Why don't we notice interference patterns when we turn on two lights in a room?

31. If light and sound are both wave phenomena, why can we hear sounds around a corner but cannot see around a corner?

32. Approximately how narrow should a slit be for the diffraction of visible light to be observable?

33. Blue light is used to form a single-slit diffraction pattern on a screen. As the slit is made wider, does the separation of the bright bands on the screen decrease, increase, or remain the same? Explain.

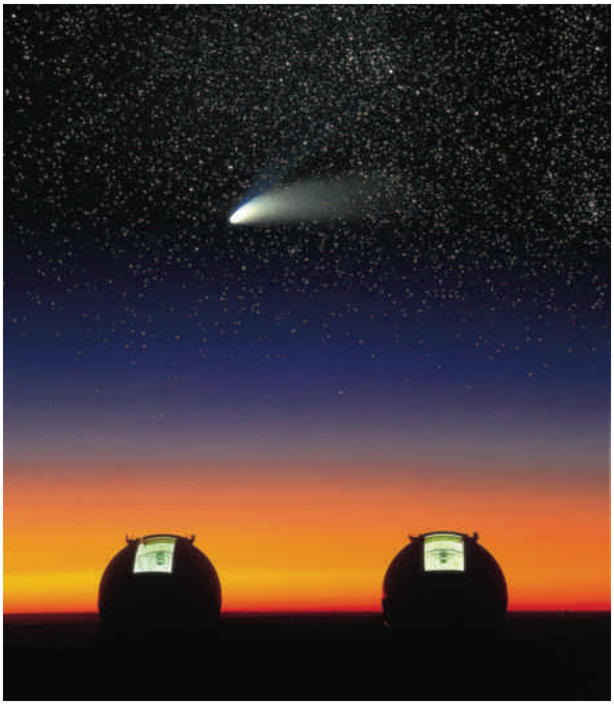
34. Would orange light or blue light produce the wider diffraction pattern? Why?

35. Would a slit with a width of 300 nanometers or of 400 nanometers produce a wider diffraction pattern when illuminated by light of the same wavelength? Why?

36. Which of the following single-slit diffraction experiments would produce the wider diffraction pattern: 800-nanometer light passing through a 500-nanometer-wide slit, or 450-nanometer light passing through a 400-nanometer-wide slit? Why?

37. Why can't an ordinary microscope using visible light be used to observe individual molecules?

38. A common technique used by astronomers for overcoming diffraction limits is to electronically combine the light from more than one telescope. This effectively increases the diameter of the aperture to the distance between the telescopes. If the signals from two 5-meter-diameter telescopes located 100 meters apart were being combined when one of the telescopes stopped functioning, by what factor would the minimum resolvable angle be increased?



David Nunuk/SPL/Photo Researchers, Inc.

39. Will you observe multicolored patterns if you illuminate a thin soap film with monochromatic light? Why?

40. A thin film of oil on top of a bucket of water produces multicolored patterns. However, a bucket full of oil produces no such effect. Explain the difference.

41. Assume that you have the thinnest film that strongly reflects red light. Would you need to make the film thinner or thicker to completely reflect blue light? Why?

42. You are coating glass with a film of higher index of refraction. You make the thinnest film that will produce a strong reflection for a particular monochromatic light source. You then gradually increase the film's thickness until you find another strong reflection. How many times thicker is this film than the original?

43. A glass pane with index of refraction 1.5 is coated with a thin film of a material with index of refraction 1.6. The coating is as thin as possible to produce maximum reflection for blue light. If this same material is used to coat a different kind of glass with index of refraction 1.9, the light reflected from the back surface of the film now experiences an inversion. Does the coating have to be thicker or thinner in this case to produce strong reflection? Explain.

44. The office workers in a skyscraper complain that the morning sun shines too brightly into their work areas. The problem is resolved by applying a thin film to each windowpane. The film has an index of refraction smaller than the glass and is designed to reflect yellow light when applied to the glass. If a sheet of this film is held in front of a yellow spotlight, would any of the light pass through the film? Explain.

Phil Jude/SPL/Photo Researchers, Inc.

45. A thin film in air strongly reflects orange light. Will it still reflect orange light when it is placed in water?

46. A thin, transparent film strongly reflects yellow light in air. What does the film do when it is applied to a glass lens that has a higher index of refraction than the film?

47. If all the labels had come off the sunglasses in the drug store, how could you tell which ones were polarized?

48. Can sound waves be polarized?

49. The digital displays at fuel pumps often use liquid crystal displays (LCDs) to show the price. Because the light from LCDs is polarized, they can often be impossible to read while wearing Polaroid sunglasses. What could you do to read the display without removing your glasses?

50. How could you use Polaroid sunglasses to tell whether light from the sky is polarized?

51. How would you distinguish a hologram from a flat transparency?

52. If each point on a holographic film contains the entire image, what is gained by making the hologram larger?

53. What kind of light is required to make a hologram of a three-dimensional object?

54. What kind of light is required to display a hologram?

55. To gather enough light to expose the film, long time exposures are often necessary to make holograms of inanimate objects. Why is a very powerful laser required to make a hologram of a person's face?

56. Which of the following phenomena does not show a difference between the wave theory and particle theory of light: reflection, refraction, interference, diffraction, or polarization?

Exercises

57. What is the speed of light in glass with an index of refraction of 1.6?

58. What is the speed of light in water?

59. The speed of light in diamond is 1.24×10^8 m/s. What is the index of refraction for diamond?

60. Zircon is sometimes used to make fake diamonds. What is its index of refraction if the speed of light in zircon is 1.6×10^8 m/s?

61. If it takes light 5 ns (1 nanosecond $= 10^{-9}$ s) to travel 1 m in an optical cable, what is the index of refraction of the cable?

62. If an optical cable has an index of refraction of 1.5, how long will it take a signal to travel between two points on opposite coasts of the United States separated by a distance of 5000 km?

63. The index of refraction for red light in material X is measured at 1.80. Blue light travels 5×10^6 m/s slower than red light in this material. What is the index of refraction for blue light in material X?

64. For crown glass, the index of refraction for violet light is 1.532 and the index of refraction for red light is 1.515. How much faster is red light than violet light in this medium?

65. What is the wavelength of the radio signal emitted by an AM station broadcasting at 1420 kHz? Radio waves travel at the speed of light.

66. What is the wavelength of light that has a frequency of 5×10^{14} Hz?

67. The red light from a helium–neon laser has a wavelength of 633 nm. What is its frequency?

68. What is the frequency of the yellow light with a wavelength of 590 nm that is emitted by sodium lamps?

69. What is the wavelength of the red light from a helium–neon laser when it is in glass with an index of refraction of 1.6? The wavelength in a vacuum is 633 nm.

70. A transparent material is known to have an index of refraction equal to 1.9. What is the wavelength of light in this material if it has a wavelength of 650 nm in a vacuum?

71. Light from a sodium lamp with a wavelength in a vacuum of 590 nm enters diamond in which the speed of light is 1.24×10^8 m/s. What is the wavelength of this light in diamond?

72. What is the wavelength of light in water if it has a frequency of 6.6×10^{14} Hz?

73. For distant objects, the angular size in degrees can be approximated as $57° \times w/d$, where w is the width of the object and d is its distance. What is the angular separation of the headlights on a car 10 km away if the headlights are 1.2 m apart?

74. The minimum angular separation in arc seconds ($\frac{1}{3600}$ degree) is found by first finding the ratio of the wavelength of light to the diameter of the aperture and then multiplying by 2.5×10^5. Using visible light with a wavelength of 550 nm, calculate the minimum angular separation for an eye with a pupil size of 5 mm.

75. Using the information in Exercise 74, find the theoretical resolution of a telescope with a 10-m-diameter mirror for visible light at 550 nm.

76. What is the theoretical resolution of a radio telescope with a 10-m-diameter collecting dish for radio waves with a wavelength of 21 cm? (See Exercise 74.)

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77. What is the thinnest soap film that will strongly reflect light with a wavelength of 400 nm in the film?

78. What is the thinnest soap film that will strongly reflect red light from a helium–neon laser? The wavelength of this light is 633 nm in air and 470 nm in soapy water.

79. You are coating a glass lens of index of refraction 1.6 with a film of material of index of refraction 1.7. You start with the thinnest film possible that creates a strong reflection for 500-nm light. You gradually increase the film thickness until you again get strong reflection. What is the thickness of the film now?

80. Repeat Exercise 79 for a glass lens of index of refraction 1.8.