CHAPTER 19 Diffraction and Interference of Light

In the Eyes of the Beholder

The South American Morpho butterfly has a unique and beautiful coloration. In daylight its wings appear a brilliant, metallic, iridescent blue. What characteristic of light could explain this unusual coloration?

Chapter Outline

19.1 WHEN LIGHT WAVES INTERFERE
- The Two-Slit Interference Pattern
- Measuring the Wavelength of a Light Wave
- Single-Slit Diffraction

19.2 APPLICATIONS OF DIFFRACTION
- Diffraction Gratings
- Resolving Power of Lenses

You have seen that dyes and pigments produce colors when they absorb some wavelengths of light while transmitting or reflecting others. In prisms and raindrops, different wavelengths are bent through different angles. The colors in peacock tails, mother-of-pearl shells, and soap films are due to interference in thin films discussed in Chapter 16. None of these methods produces the colors in beetles and the wings of butterflies, which are some of the most beautiful in nature.

✓ Concept Check

The following terms or concepts from earlier chapters are important for a good understanding of this chapter. If you are not familiar with them, you should review them before studying this chapter.
- superposition of waves, wavelength, Chapters 14, 16

Objectives

- define diffraction of light.
- display an understanding of how light falling on two slits produces a pattern of dark and bright bands on a screen.
- understand the geometrical interpretation of two-slit interference.
- demonstrate an ability to calculate the wavelength of light from measurements of the two-slit interference pattern.
- explain geometrically how single-slit diffraction patterns occur; use the derived equation to relate the pattern width to slit width and light wavelength.

19.1 WHEN LIGHT WAVES INTERFERE

An English physician, Thomas Young (1773–1829), became interested in optics when he studied the human eye. Young's early medical studies of the human voice led him to investigate waves. The insights he gained he applied to the understanding of wave interference in oceans and lakes. He read Newton's book on optics and became convinced that Newton's results could be explained if light were a wave of almost unimaginably small wavelength. In 1801, he developed an experiment that would allow him to make a precise measurement of that wavelength.

The Two-Slit Interference Pattern

Diffraction is the bending of light around the edges of barriers.

The Italian, Francesco Maria Grimaldi (1618–1663) first noted that the edges of shadows are not perfectly sharp. He named the slight spreading of light waves diffraction. **Diffraction** is the bending of waves around the edges of barriers. The Dutch scientist Christiaan Huygens (1629–1695) proposed a model to explain diffraction. According to Huygens, you can replace the crest of any wave by series of equally-spaced wave sources, each producing new waves in step with one another. Figure 19–1 shows how Huygens' wavelets explain diffraction.

Huygens' model may explain diffraction, but does that mean light has to be a wave? Young's experiment gave additional evidence of the wave nature of light. Young allowed light to fall on two closely-spaced narrow slits. The light passing through each slit was spread out, or diffracted. The spreading light from the two slits overlapped. When the light fell on an observing screen, the overlap did not produce extra light, but a pattern of bright and dark bands called **interference fringes.** Young explained that these bands were the result of constructive and destructive interference of the light waves from the two slits.

Young used a **monochromatic** (mahn uh croh MAT ik) light source, one that emits light of only one wavelength. He placed a narrow slit in front of the source. This slit allowed light from only a small part of the source to pass through. As a result, the waves were not only the same wavelength, but all were in step. That is, they were **coherent.** The

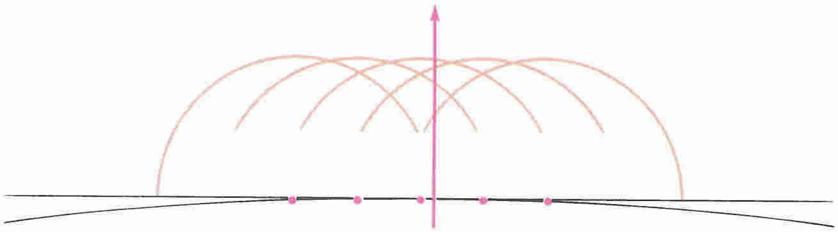


FIGURE 19–1. According to Huygens, the crest of each wave could be thought of as a series of point sources.

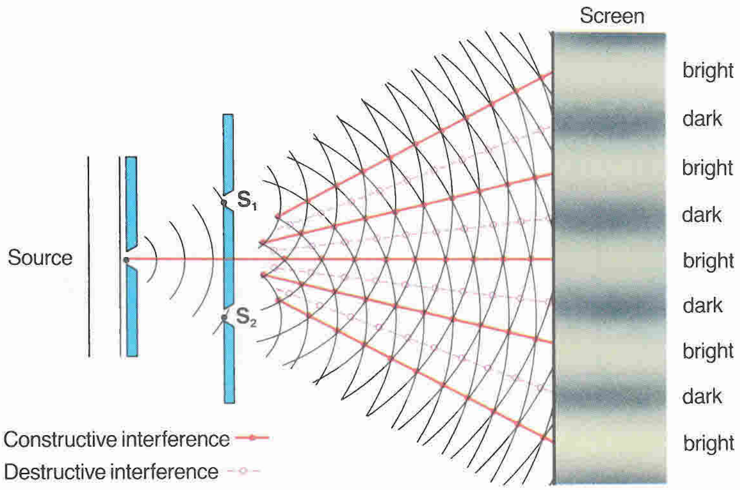


FIGURE 19–2. The diffraction of monochromatic light through a double slit produces bright and dark bands on a screen.

waves spread after passing through the single slit and fell on the double slit. The double slit acted as two sources of new circular waves. In Figure 19–2, the semicircles represent wave crests moving outward from the slits. Midway between the crests are the troughs. The waves from the two sources interfere constructively at points where two crests overlap. They interfere destructively where a crest and a trough meet.

When monochromatic light is used, Figure 19–3a, b, bright bands of light appear at points where the constructive interference occurs on the screen. One bright band appears at the center of the screen. On either side of the central band are bright bands corresponding to the other points of constructive interference. Between the bright bands are dark areas located where destructive interference occurs on the screen.

When white light is used in a double-slit experiment, Figure 19–3c, colored spectra are seen instead of bright and dark bands. The positions of the constructive and destructive interference bands depend on the wavelength of the light. All wavelengths interfere constructively in the central bright band, so that band is white. The positions of the other bands depend on the wavelength, so the light is separated by diffraction into a spectrum of color at each band.

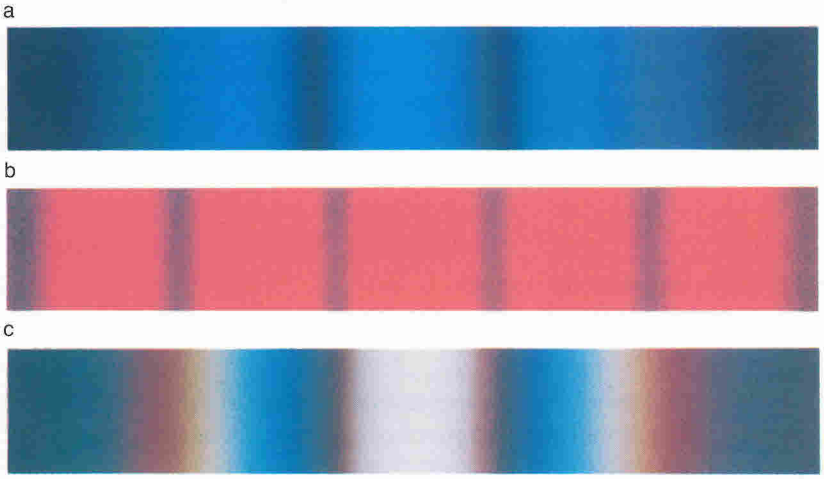
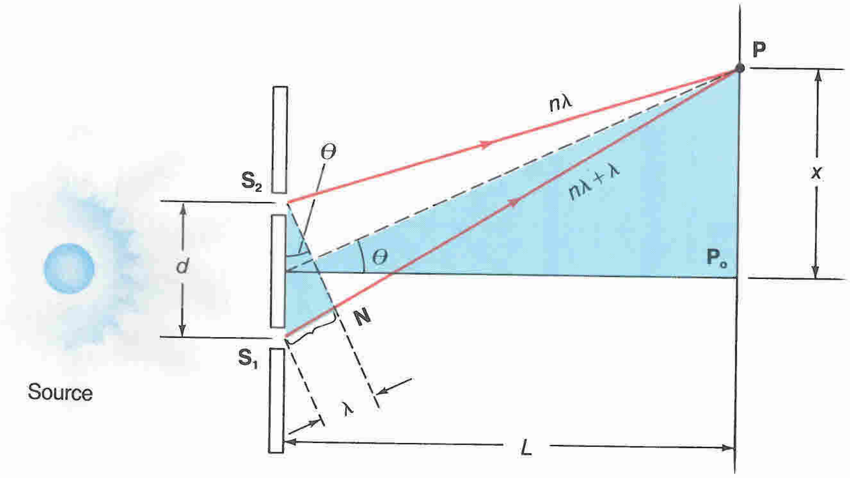


FIGURE 19–3. The diffraction of a monochromatic light source produces an interference pattern on the screen resulting in a pattern, such as the one shown for blue light (a), and for red light (b). The diffraction of white light produces bands of colors (c).

FIGURE 19–4. Schematic diagram for analysis of double-slit interference. The diagram is not to scale. Typically, L is about 10^5 times the slit separation, d.



When white light passes through a double slit, a continuous spectrum is formed.

Measuring the Wavelength of a Light Wave

Young used the double-slit experiment to make the first precise measurement of the wavelength of light. The central bright band that falls on the screen at point $\mathbf{P}_0$ in Figure 19–4 does not depend on the wavelength, so another bright band is used. The first bright band on either side of the central band is called the first-order line. It falls on the screen at point **P.** The band is bright because light from the two slits interferes constructively. The two path lengths differ by one wavelength. That is, the distance $\mathbf{PS}_1$ is one wavelength longer than $\mathbf{PS}_2$.

To follow Young's experiment using Figure 19–4, you must understand that the drawing is not to scale. The length **PO** (L) is really very much greater than $\mathbf{S}_1\mathbf{S}_2$ (d). It is necessary to distort the diagram so the details close to the slit can be shown. To measure the wavelength, Young first measured the distance between $\mathbf{P}_0$ and **P,** labeled x in the diagram. The distance between the screen and the slits is L, and the separation of the two slits is d. In the right triangle $\mathbf{NS}_1\mathbf{S}_2$, the side $\mathbf{S}_1\mathbf{N}$ is the length difference of the two paths. $\mathbf{S}_1\mathbf{N}$ is one wavelength, λ, long. The lines from the slits to the screen are almost parallel because length L is so much larger than d. Thus the lines $\mathbf{NS}_2$ and **OP** are perpendicular. The triangle $\mathbf{NS}_1\mathbf{S}_2$ is similar to triangle $\mathbf{PP}_0\mathbf{O}$. Therefore, the ratio of the corresponding sides of these similar triangles is the same. That is,

$$\frac{x}{L} = \frac{\lambda}{d}.$$

Solving this equation for λ gives

$$\lambda = \frac{xd}{L}.$$

The wavelengths of light waves can be measured with considerable precision using double-slit interference patterns. It is not unusual for wavelength measurements to be precise to four digits.

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Example Problem

Wavelength of Light

Red light falls on two narrow slits 0.0190 mm apart. A first-order bright line is 21.1 mm from the central bright line on a screen 0.600 m from the slits. What is the wavelength of the red light?

Given: $d = 1.90 \times 10^{-5}$ m
$x = 21.1 \times 10^{-3}$ m
$L = 0.600$ m

Unknown: λ
Basic equation: $\lambda = xd/L$

Solution: $$\lambda = xd/L = \frac{(21.1 \times 10^{-3}\text{ m})(1.90 \times 10^{-5}\text{ m})}{(0.600\text{ m})}$$
$$= 6.68 \times 10^{-7}\text{ m} = 668\text{ nm}$$

Practice Problems

1. Violet light falls on two slits separated by 1.90×10^{-5} m. A first-order line appears 13.2 mm from the central bright line on a screen 0.600 m from the slits. What is the wavelength of the violet light?
2. Yellow-orange light from a sodium lamp of wavelength 596 nm is used instead of the violet light of Problem 1. The slit separation and distance to the screen are not changed. What is the distance from the central line to the first-order yellow line?
3. A physics class uses a laser with a known wavelength of 632.8 nm in a double-slit experiment. The slit separation is unknown. A student places the screen 1.000 m from the slits and finds the first-order line 65.5 mm from the central line. What is the slit separation?
4. ▶ Using the double-slit apparatus of Problem 3, the student measures the wavelength of an unknown green light. The first-order line is 55.8 mm from the central line. What is the wavelength of the light?

Single-Slit Diffraction

As you are leaving school, you walk by the open door of the band rehearsal room. You hear the music, however, long before you can see the players through the door. Sound seems to have bent around the edge of the door, while light has traveled only in a straight line. They are both waves—why don't they act the same? Actually, they do. As Grimaldi first noted, the spreading, or diffraction, is there in both cases, but, because of light's much smaller wavelengths, the effect is tiny.

When light passes through a small single opening, a series of bright and dark interference bands appears. Instead of the equally-spaced, bright bands produced by two slits, the pattern from a single slit has a wide, bright central band with dimmer bright bands on either side.

To observe single-slit diffraction, fold a small piece of paper and cut a narrow slit along its folded edge. Unfold the paper and look through the slit at a light source. You will see an interference pattern. You can vary the width of the slit by pulling on the opposite edges of the paper. Observe the effect the change in slit width has on the pattern.

POCKET LAB

LASER SPOTS

Turn on the laser so that it makes a spot on the center of the movie screen. What do you expect should happen to the spot if you were to put a piece of screen door screen in the center of the beam? Explain your prediction. Try it. What really happened? Use the wave theory to explain your results.

F.Y.I.

You can produce single-slit diffraction by holding the index and middle fingers of one hand together and looking at a bright light through the space between them. Then press the fingers together to change the opening size and observe how the diffraction pattern changes.

What causes the diffraction pattern? Figure 19–6 shows monochromatic light from a distant source falling on a slit of width w. Because the light is so far away, a crest in the wave strikes all points of the slit at the same time. Light coming through the slit falls on a screen placed a distance L from the slit. There is a wide central band, $\mathbf{P}_0$. What waves contribute to the central band? For this discussion we have divided the width of the slit into twelve parts. Because L is so much larger than w, all rays falling on the slit are, in effect, the same distance from $\mathbf{P}_0$. The distances $\mathbf{AP}_0$, $\mathbf{BP}_0$, $\mathbf{CP}_0$, and L are equal, and the crests of all waves arrive at $\mathbf{P}_0$ at the same time. Thus, the central band is bright. $\mathbf{P}_\mathrm{p}$ is any point on the screen.

As you move away from the center, the distance **CP** becomes larger than **AP.** When you reach point $\mathbf{P}_\mathrm{d}$, $\mathbf{CD} = \lambda$, so the distance $\mathbf{CP}_\mathrm{d}$ is exactly one wavelength longer than $\mathbf{AP}_\mathrm{d}$. Therefore, waves from point **1′** travel one-half wavelength longer than those from point **1.** They destructively interfere. The same is true for points **2′** and **2, 3′** and **3,** and so on down the slit. A wave from one point of the slit is canceled by a wave from another. The result is darkness.

If you go either closer to or farther away from the center, the distance **CP** is not exactly one wavelength longer and some waves no longer cancel. Thus the darkness is not complete. Consider going out far enough to make $\mathbf{CP}_\mathrm{p}$ two wavelengths (2λ) larger than $\mathbf{AP}_\mathrm{p}$. Then there is a second dark band. Third, fourth, and higher bands are reached when the difference in path length is 3λ, 4λ, and so forth.

Light passing through a single slit produces a series of bright and dark bands equally spaced around a bright central band.

What is the distance from $\mathbf{P}_0$ to the first dark band, $\mathbf{P}_\mathrm{d}$? If angle θ is very small, triangles **CDA** and $\mathbf{BP}_\mathrm{d}\mathbf{P}_0$ are similar. From triangle **CDA,**

$$\sin\theta = \frac{\lambda}{w}.$$

In the same way, consider triangle $\mathbf{BP}_\mathrm{d}\mathbf{P}_0$. Because $\mathbf{BP}_\mathrm{d}$ and L are nearly equal, we can say

$$\sin\theta = \frac{x}{BP_\mathrm{d}} = \frac{x}{L}.$$

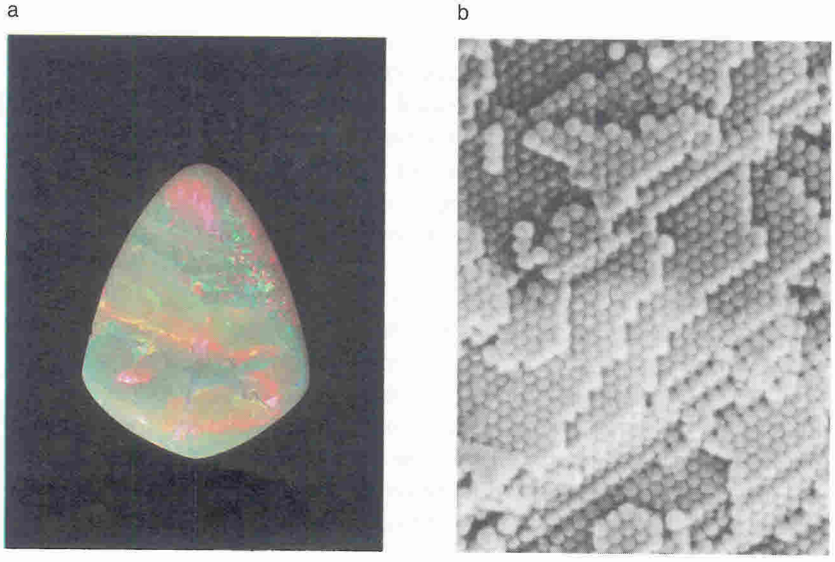


FIGURE 19–5. The beautiful colors of this opal (a) are produced by diffraction from ridges on the surface of the gem (b).

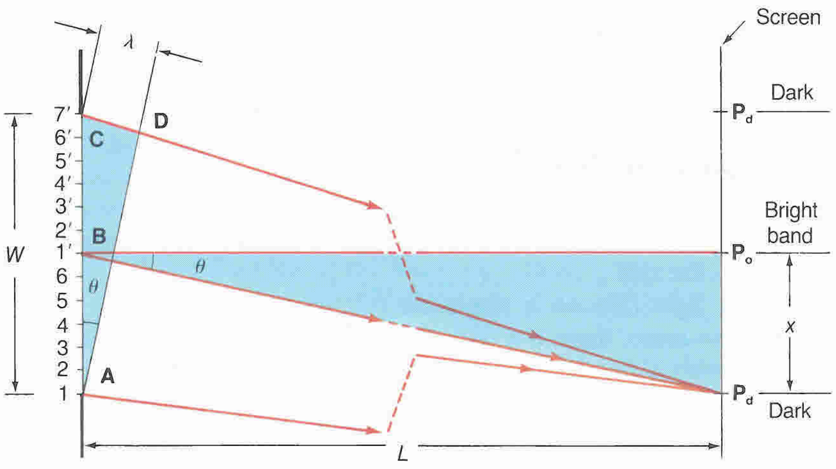


FIGURE 19–6. Schematic diagram for analysis of single-slit diffraction. The diagram is not to scale. Typically *L* is 10^5 times the slit width.

Therefore,

$$\frac{\lambda}{w} = \frac{x}{L}, \text{ or } x = \frac{\lambda L}{w}.$$

Notice that the smaller the slit width, *w,* the larger the distance, *x*. That is, the smaller the slit, the wider the central band. As a model, imagine a beam of light shining through an open door. The beam has sharp edges because the interference fringes are very close together and almost unnoticeable. As you close the door, the beam becomes smaller. If the opening is reduced to a few wavelengths wide, the edges of the beam become less well defined. The interference fringes become more widely spaced and more visible, making the edges appear fuzzy. Thus, sharp shadows are cast only by large openings. The pattern width also depends on wavelength. For a fixed slit width, the shorter the wavelength, the narrower the pattern, Figure 19–7.

Diffraction is at a maximum when the width of the opening is equal to the wavelength of light.

Example Problem

Single-Slit Diffraction

Monochromatic orange light of wavelength 605 nm falls on a single slit of width 0.095 mm. The slit is located 85 cm from a screen. How far from the center of the central band is the first dark band?

Given: slit width,
$w = 0.095$ mm
distance to screen,
$L = 85$ cm
light wavelength,
$\lambda = 605 \text{ nm} = 6.05 \times 10^{-7}$ m

Unknown: separation between central band and dark band, *x*

Basic equation: $x = \frac{\lambda L}{w}$

Solution: $x = \frac{\lambda L}{w} = \frac{(6.05 \times 10^{-7}\text{ m})(0.85\text{ m})}{9.5 \times 10^{-5}\text{ m}} = 5.4\text{ mm}$

F.Y.I.

Thomas Young was a child prodigy. He could read at age two, and by age four, he had read the Bible twice. He studied many languages and played a variety of musical instruments. He also spent time deciphering Egyptian hieroglyphics.

Practice Problems

5. Monochromatic green light of wavelength 546 nm falls on a single slit of width 0.095 mm. The slit is located 75 cm from a screen. How far from the center of the central band is the first dark band?

6. Light from a He-Ne laser ($\lambda = 632.8$ nm) falls on a slit of unknown width. A pattern is formed on a screen 1.15 m away where the first dark band is 7.5 mm from the center of the central bright band. How wide is the slit?

7. Yellow light falls on a single slit 0.0295 mm wide. On a screen 60.0 cm away, there is a dark band 12.0 mm from the center of the bright central band. What is the wavelength of the light?

8. White light falls on a single slit 0.050 mm wide. A screen is placed 1.00 m away. A student first puts a blue-violet filter ($\lambda = 441$ nm) over the slit, then a red filter ($\lambda = 622$ nm). The student measures the width of the central peak, that is, the distance between the two dark bands.

a. Will the band be wider with the blue-violet or the red filter?

b. Find the width for the two filters.

CONCEPT REVIEW

1.1 Two very narrow slits are cut close to each other in a large piece of cardboard. They are illuminated by monochromatic red light. A sheet of white paper is placed far from the slits, and a pattern of bright and dark bands is seen on the paper. Explain why some regions are bright while others are dark.

1.2 Sketch a graph that shows the pattern seen.

1.3 Sketch what happens to the pattern if the red light is replaced by blue light.

1.4 **Critical Thinking:** One of the slits is covered so no light can get through. What happens to the pattern?

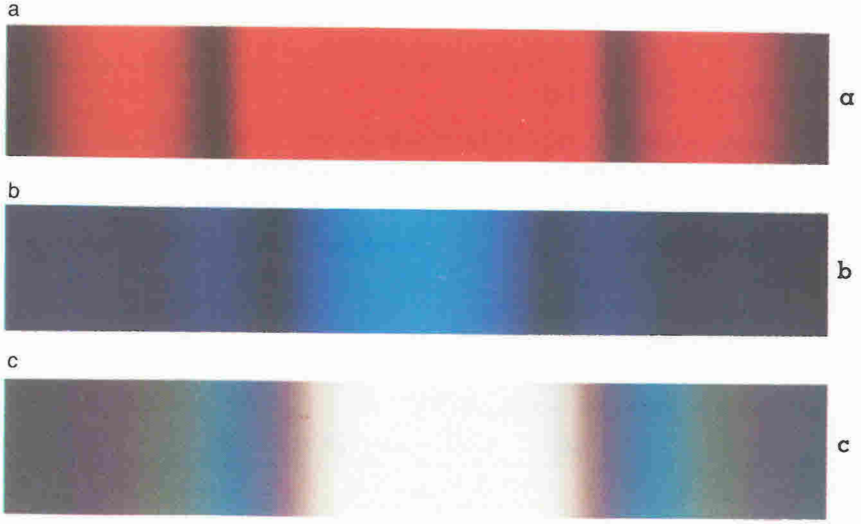


FIGURE 19–7. These diffraction patterns for red light (a), blue light (b), and white light (c) were produced with a slit of width 0.02 cm. Red light has a longer wavelength than blue light.

PHYSICS LAB Wavelengths of Colors

Purpose

To measure accurately the wavelength of four colors of light.

Materials

- meter stick
- index card
- 40-W straight filament light
- ball of clay
- tape
- diffraction grating

Procedure

1. Cut the index card (lengthwise) into four equal strips.
2. Write the letters "O" (orange), "Y" (yellow), "G" (green), and "B" (blue) on the strips of index card.
3. Place the ball of clay 1.0 m in front of the lamp. Use the ball of clay to support the diffraction grating.
4. Plug in the lamp and turn off the room lights.
5. When you look through the diffraction grating, you should see the colors to the sides of the bulb. If you do not see the colors to the sides, then rotate the diffraction grating (90 °) until you do.
6. Have a lab partner move the "O" orange index card strip until it seems to be in the middle of its color. Tape the strip to the table.
7. Repeat for each of the other colored index card strips.

Observations and Data

1. What color is closest to the lamp? Suggest a reason.
2. List the order that colors occur, beginning from red.
3. Set up a data table to record x, d, and L for each of the four colors. Measure x for each index card strip (to the nearest 0.1 cm).
4. Record the value of d from the chalkboard.

Analysis

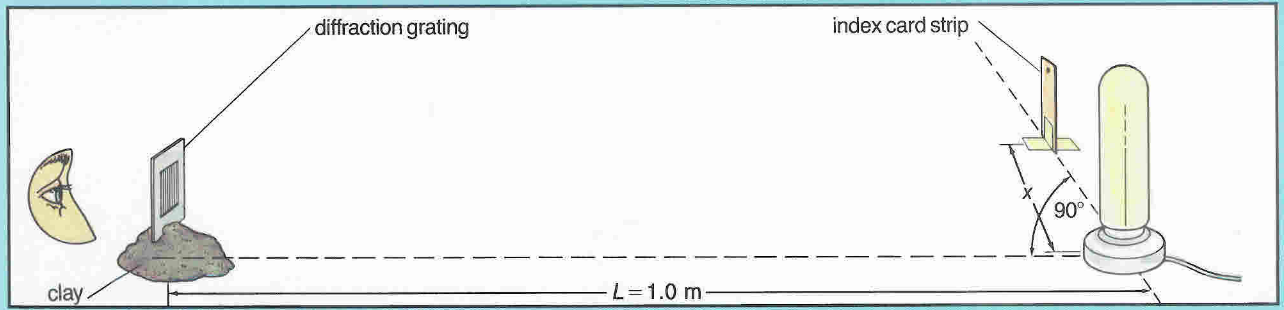
Use the following equation to estimate the wavelength for each color. Convert your answers for the wavelength to nm.

$$\lambda = xd/L$$

5. Record the value of L.

Applications

1. How could diffraction gratings be used in conjunction with telescopes?



19.2 APPLICATIONS OF DIFFRACTION

Objectives

- explain the interference pattern formed by the diffraction grating.
- understand the operation of a grating spectrometer.
- explain how diffraction effects limit the resolution of a lens.

In the Eyes of the Beholder

Many beetles and butterflies, including the *morpho* butterfly shown in the chapter-opening photo, produce their iridescent colors by means of diffraction. The butterfly's wings are covered with tiny ridges only a few hundred nanometers apart. They each diffract the light hitting them, producing interference effects. Because of the orientation of the ridges, blue is the predominant color. Some dragonfly wings have dark veins spaced in such a way that sunlight is diffracted into spectra. Such a series of slits makes the interference pattern of two slits even stronger. It is called a **diffraction grating.**

Diffraction Gratings

Although single- or double-slit diffraction can be used to measure the wavelength of light, in practice a diffraction grating, Figure 19–8, is used. Diffraction gratings are made by scratching very fine lines with a diamond point on glass. The clear spaces between the lines serve as slits. Gratings can have as many as 10 000 lines per centimeter. That is, the spacing between the lines is 10^{-6} m, or 1000 nm. Inexpensive *replica gratings* are made by pressing a thin plastic sheet onto a glass grating. When the plastic is pulled away, it contains an accurate imprint of the scratches. Jewelry can be made from replica gratings.

Gratings form interference patterns in the same way a double slit does. The bright bands are in the same location, but they are narrower, and the dark regions are broader. As a result, individual colors are not smeared out and can be distinguished more easily. This means that wavelengths can be measured more precisely than with double slits.

In Section 19.1 the equation used to calculate the wavelength of light using double-slit interference was given as

$$\frac{x}{L} = \frac{\lambda}{d}.$$

The same equation holds for a diffraction grating where d is the distance between the lines. Instead of measuring the distance from the central band to the first bright band, x, most laboratory instruments mea-

POCKET LAB

HOT LIGHTS

Plug a 100-W clear lamp into a Variac (variable power supply). Turn off the room lights. Look through a diffraction grating at the lamp as you slowly increase the power. Describe what you see. Which color(s) appear first? What happens to the brightness of previous colors as new colors are seen? What is the order of the colors?

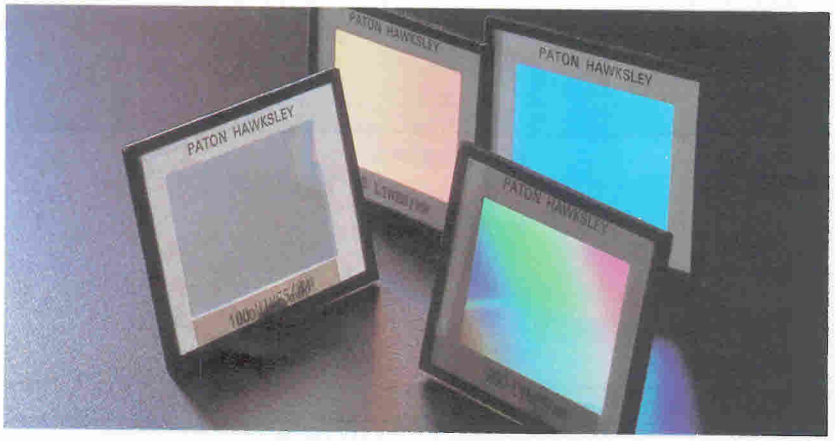


FIGURE 19–8. Diffraction gratings are used to create interference patterns to analyze light sources.

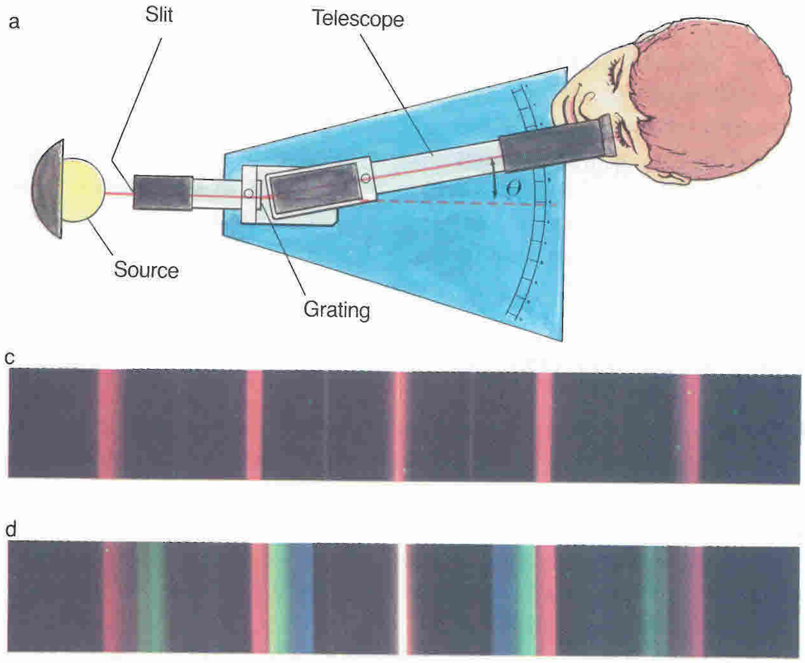


FIGURE 19–9. A spectrometer is used to measure the wavelengths of light emitted by a light source (a, b). A grating was used to produce interference patterns for red light (c) and white light (d).

sure the angle θ shown in Figure 19–4. Because x is so small with light, $\sin\theta \approx x/L$. Therefore, the wavelength can be found by measuring the angle between the central bright band and the first-order line, and using the equation

$$\boxed{\lambda = \frac{xd}{L} = d\sin\theta.}$$

The instrument used to measure light wavelengths with a diffraction grating is called a grating spectrometer, Figure 19–9. The source emits light that falls on a slit and then passes through a diffraction grating. When monochromatic red light is used, Figure 19–9c, a series of bright bands appears to the left and right of the central bright line. When white light falls on the instrument, each red band is replaced by a spectrum. The red band in the spectrum is at the same location as when monochromatic light is used. The telescope is moved until the desired line appears in the middle of the viewer. The angle θ is then read directly from the calibrated base of the spectrometer. Because d is known, λ can be calculated.

F.Y.I.

The Hubble Space Telescope was designed to resolve stars. It can resolve objects whose spacing is the equivalent to the spacing of car headlights 2500 miles away.

Resolving Power of Lenses

When light passes through the lens of a telescope, it passes through a circular hole. The lens diffracts the light just as a slit does. The smaller the lens, the wider the diffraction pattern. If the light comes from a star, the star will appear spread out. If two stars are close enough together, the images will be so blurred that a viewer cannot tell whether there are two stars or only one. The telescope can no longer resolve the images of the two stars. Lord Rayleigh set the **Rayleigh criterion** for resolution. If the central bright band of one star falls on the first dark band of the

◀ ASTRONOMY CONNECTION

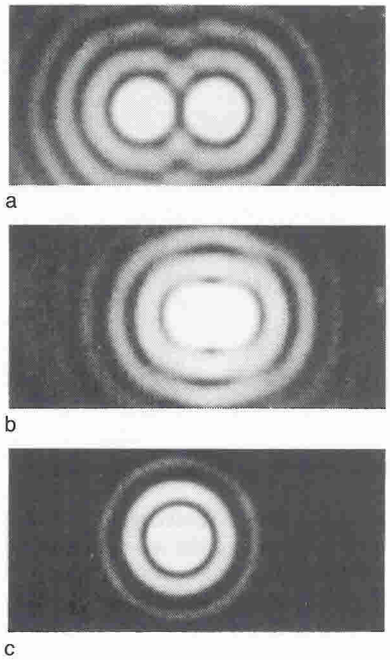


FIGURE 19–10. The diffraction patterns of two point sources (a). As the sources move closer together, the images become fuzzy (b) and eventually merge into one image (c).

second, the two stars are just resolved. That is, a viewer can tell that there are two stars and not just one.

The effects of diffraction on the resolving power of the telescope can be reduced by increasing the size of the lens. Diffraction also limits the resolving power of microscopes. The objective lens of a microscope cannot be enlarged, but the wavelength of light can be reduced. The diffraction pattern formed by blue light is narrower than that of red light. Thus biologists often use blue or violet light to illuminate microscopes.

CONCEPT REVIEW

2.1 The two slits of Concept Review Question 1.1 are replaced by very many narrow slits with the same spacing. Sketch the pattern that would now be seen on the screen.

2.2 You shine a red laser light through first one, then a second diffraction grating. Patterns of red dots are seen on a screen. The dots from one grating are spread more than those from the other. Which grating has more lines per mm?

2.3 A telescope is used to view a number of closely-spaced stars. Filters are used to select only certain colors from the starlight. In which color, red or blue, would the stars be more easily counted? Explain.

2.4 **Critical Thinking:** You are shown a spectrometer, but do not know whether it produces its spectrum with a prism or a grating. By looking at a white light spectrum, how could you tell?

Physics and technology

HOLOGRAMS

Interference properties of light are used to produce three-dimensional images called holograms. Developed by Dennis Gabor, who won the 1971 Nobel Prize in physics for his work, holograms record both the intensity and phase of light.

To make a hologram, laser light is split by a mirror into two parts. One part is directed to the object and then reflected off the object onto film. The other part goes directly to the film. The result is complex interference patterns. When the film is illuminated by laser light, the emerging light is an exact duplicate of the light reflected originally by the object. The image appears three-dimensional; you can observe it from all sides.

Because holograms are very difficult to counterfeit, holography is being used in security identification and credit cards. There is speculation that holograms may be used as part of a future United States currency. Research is being conducted to apply holograms in microscopic work, medicine, and information storage and display. Holograms may find uses in video games and displays, and motion pictures.

- What property of light, sound, and electrons enables them all to be used in making holograms?

CHAPTER 19 REVIEW

SUMMARY

19.1 When Light Waves Interfere

- Light passing through a narrow hole or slit is diffracted, or bent from a straight-line path.
- Interference between light diffracted from two closely-spaced narrow slits causes an interference pattern to appear on a distant screen.
- The wavelength of light can be measured by analyzing the double-slit interference pattern.
- When light passes through a narrow opening, diffraction causes a pattern of light and dark bands to form.
- Single slits produce diffraction patterns that are less well defined than those formed by double slits.

19.2 Applications of Diffraction

- Diffraction gratings with large numbers of evenly-spaced slits produce interference patterns that are used to measure the wavelength of light precisely.
- Diffraction limits the resolving power of lenses.

KEY TERMS

diffraction
interference fringes
monochromatic
coherent
diffraction grating
Rayleigh criterion

REVIEWING CONCEPTS

1. Why is it important that monochromatic light be used to make the interference pattern in Young's interference experiment?
2. Explain why the central bright line produced when light is diffracted by a double slit cannot be used to measure the wavelength of the light waves.
3. Describe how you could use light of a known wavelength to find the distance between two slits.
4. Why is blue light used for illumination in an optical microscope?
5. Why is the diffraction of sound waves more familiar in everyday experience than the diffraction of light waves?
6. In each of the following examples, state whether the color is produced by diffraction, refraction, or the presence of pigments: (a) soap bubbles (b) peacock tails (c) rose petals (d) mother of pearl (e) oil films (f) blue jeans (g) the halo around the moon on a night when there is a high, thin cloud cover.
7. As monochromatic light passes through a diffraction grating, what is the difference in path length between two adjacent slits and a dark area on the screen?
8. When white light is passed through a grating, what is seen on the screen? Why are no dark areas seen?
9. Why do diffraction gratings have a large number of slits? Why are the slits so close together?
10. Why would a small diameter telescope not be able to resolve the images of two closely-spaced stars?

APPLYING CONCEPTS

1. Suppose you are using a double slit to measure light wavelength precisely. It is easier to measure a larger than a smaller distance precisely. How can the value of *x* be increased?
2. Two loudspeakers are placed 1.0 m apart on the edge of a stage. They emit sound of two wavelengths, 1.0 m long and 2.0 m long.
   - **a.** If you are sitting 3.0 m from the stage, equidistant from the speakers, do you hear loud or quiet sounds for each of the wavelengths? Explain.
   - **b.** If you sit 0.50 m from one speaker and 1.5 m from the other, what do you hear for each wavelength? Explain.
3. How can you tell whether an interference pattern is from a single slit or a double slit?
4. Describe the changes in a single-slit pattern as slit width is decreased.
5. Does interference aid or hinder radio reception? Explain.

6. Does diffraction aid or hinder the viewing of images in a microscope? Explain.

7. For a given grating, which color of light produces a bright line closest to the central bright line?

8. What changes occur in the characteristics of the interference patterns formed by a diffraction grating containing 10^4 lines/cm and one having 10^5 lines/cm?

9. Using Figure 16–1 or Figure 26–8, decide for which part of the electromagnetic spectrum a picket fence could possibly be used as a diffraction grating.

PROBLEMS

19.1 When Light Waves Interfere

1. Using a compass and ruler, construct a scale diagram of the interference pattern that results when waves 1 cm in length fall on two slits 2 cm apart. The slits may be represented by two dots spaced 2 cm apart and kept to one side of the paper. Draw a line through all points of reinforcement. Draw dotted lines through all nodal lines.

2. A radio station uses two antennas and broadcasts at 600 kHz. Radio waves travel at the speed of light. The waves from the two antennas are kept in step.

- **a.** What is the wavelength of the signals emitted by the station?
- **b.** The occupants of a home located 17 500 m from one antenna and 19 500 m from the other antenna have their receiver tuned to the station. Is the reception good or poor? Explain.

3. Light falls on a pair of slits 1.90×10^{-3} cm apart. The slits are 80.0 cm from the screen. The first-order bright line is 1.90 cm from the central bright line. What is the wavelength of the light?

4. Light of wavelength 542 nm falls on a double slit. First-order bright bands appear 4.00 cm from the central bright line. The screen is 1.20 m from the slits. How far apart are the slits?

5. A lecturer is demonstrating two-slit interference with sound waves. Two speakers are used, 4.0 m apart. The sound frequency is 325 Hz and the speed of sound is 343 m/s. Students sit in seats 4.5 m away. What is the spacing between the locations where no sound is heard because of destructive interference?

6. Monochromatic light passes through a single slit with a width of 0.010 cm and falls on a screen 100 cm away. If the distance from the center of the pattern to the first band is 0.60 cm, what is the wavelength of the light?

7. Light with a wavelength of 4.5×10^{-5} cm passes through a single slit and falls on a screen 100 cm away. If the slit is 0.015 cm wide, what is the distance from the center of the pattern to the first dark band?

8. Monochromatic light with a wavelength of 400 nm passes through a single slit and falls on a screen 90 cm away. If the distance of the first-order dark band is 0.30 cm from the center of the pattern, what is the width of the slit?

▶ **9.** Sound waves of frequency 550 Hz enter a window 1.2 m wide. The window is in the exact center of one wall of a theater 24 m × 12 m. The window is 12 m from the opposite wall, along which is a row of seats occupied by people. The theater is acoustically prepared to prevent the reflection of sound waves, and the speed of sound is 330 m/s. Two people in the row along the wall hear no sound. Where are they sitting?

19.2 Applications of Diffraction

10. A good diffraction grating has 2.50×10^3 lines/cm. What is the distance between two lines in the grating?

11. Using grating with a spacing of 4.00×10^{-4} cm, a red line appears 16.5 cm from the central line on a screen. The screen is 1.00 m from the grating. What is the wavelength of the red light?

12. A spectrometer uses a grating with 12 000 lines/cm. Find the angles at which red light, 632 nm, and blue light, 421 nm, have the first-order bright bands.

▶ **13.** The ridges in the *Morpho* butterfly wing in the chapter-opening photograph are spaced about 2.2×10^{-7} m apart. Explain how they could cause the wing to appear iridescent blue.

▶ **14.** Janet uses a 33-1/3 rpm record as a diffraction grating. She shines a laser, $\lambda = 632.8$ nm, on the record. On a screen 4.0 m from the record, a series of red dots 21 mm apart are seen.

- **a.** How many ridges are there in a centimeter along the radius of the record?
- **b.** She checks her results by noting that the ridges came from a song that lasted 4.01 minutes and took up 16 mm on the record. How many ridges should there be in a centimeter?

15. A camera with a 50-mm lens set at *f*/8 aperture has an opening 6.25 mm in diameter. Suppose this lens acts like a slit 6.25 mm wide. For light with $\lambda = 550$ nm, what is the resolution of the lens, the distance from the middle of the central bright band to the first-order dark band? The film is 50 mm from the lens.

16. The owner of the camera in Problem 15 tries to decide which film to buy for it. The expensive one, called fine-grain film, has 200 grains/mm. The less costly, coarse-grain film has only 50 grains/mm. If the owner wants a grain to be no smaller than the width of the central bright band calculated above, which film should be purchased?

17. Suppose the Hubble Space Telescope, 2.4 m in diameter, is in orbit 100 km above Earth and is turned to look at Earth. If you ignore the effect of the atmosphere, what is the resolution of this telescope? Use $\lambda = 500$ nm.

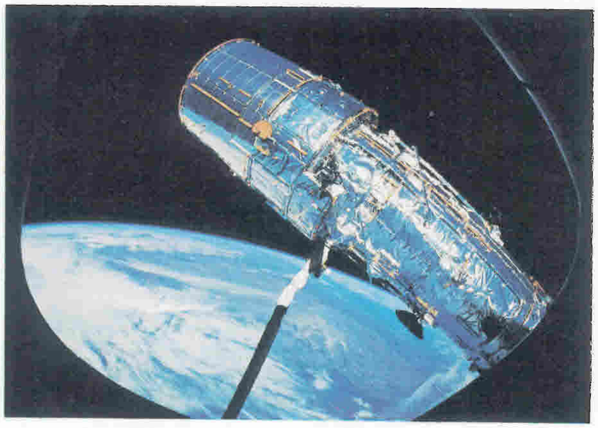


FIGURE 19–11. Hubble Telescope

18. The image formed on the retina of the eye shows the effect of diffraction. The diameter of the iris opening in bright light is 3.0 mm. For green light, 545 nm wavelength, find the resolution of the eye. That is, find the distance from the center of the central band to the dark band. Assume the distance from iris to retina is 2.5 cm.

▶ **19.** Cone cells in the retina are about 1.5 μm apart. On how many cone cells does the image found in Problem 18 fall? Would the eye's resolution be better if the pupil were much larger, like the 10 mm diameter of an eagle's eye? Explain.

USING LAB SKILLS

1. In the Physics Lab on page 399, you estimated the wavelengths of several colors of light based on the interference effect. Take a new measurement of *x* when the *L* value is 2.0 m instead of 1.0 m. How does the relative error of your new calculated value compare with that for your original value.

2. Describe which colors are "cooler" and which colors correspond to higher temperatures. Would your choices of cool and warm colors agree with that of an artist?

THINKING PHYSIC-LY

When you look at light reflected in a compact disk you see one or more rainbow-like spectra. What is the cause of this beautiful display?