On the Right Wavelength

Beetles can be annoying pests to gardeners, but it is still easy to admit how beautiful some of them can be. In daylight, the hard back of this ground beetle appears to be a mix of brilliant, metallic, iridescent colors. What characteristic of light could explain this unusual effect?

➡ *Look at the text on page 452 for the answer.*

spectrometer

DIFFRACTION GRATING

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

light

HOLOGRAM
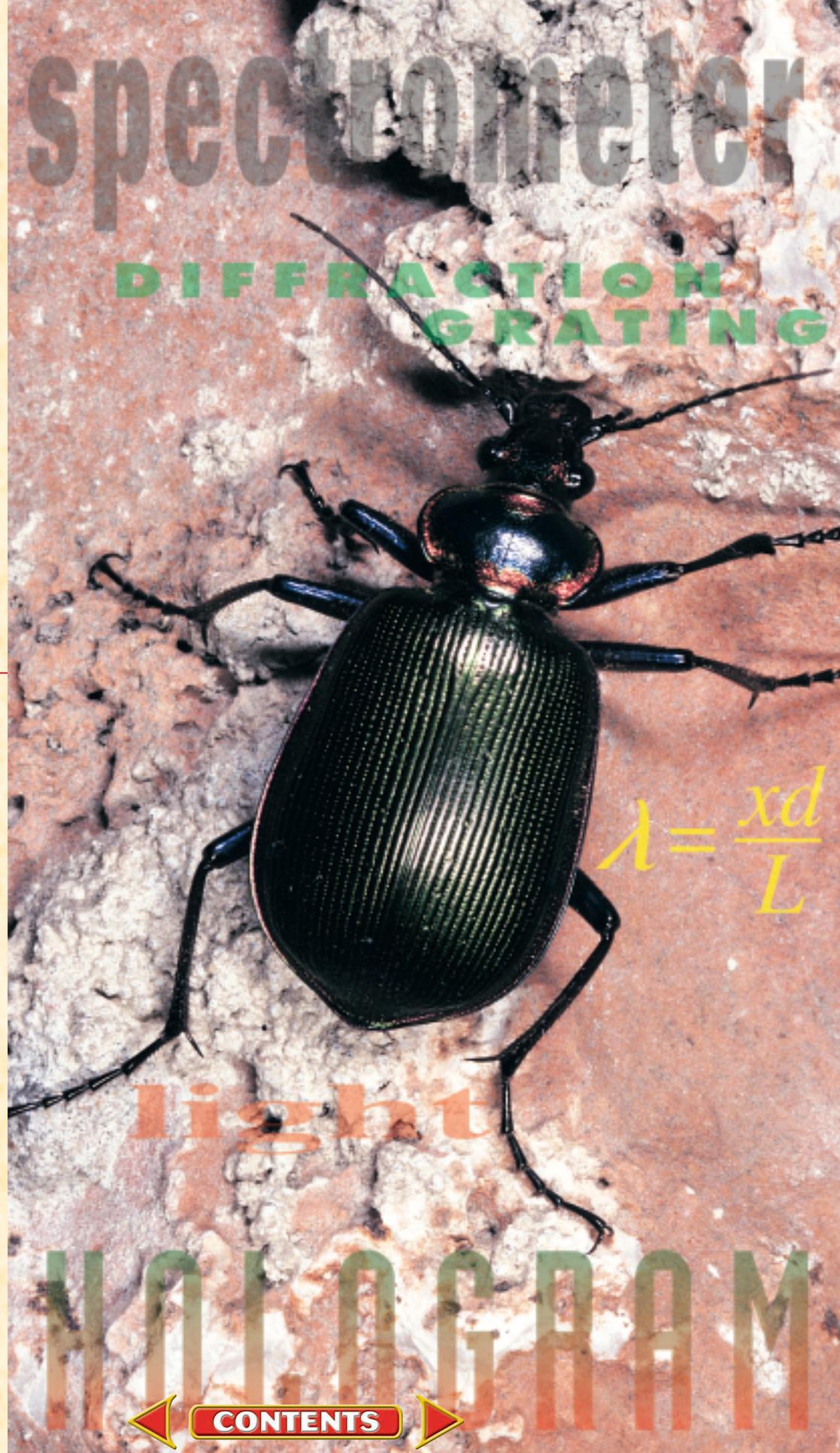
19 Diffraction and Interference of Light

You have seen that dyes and pigments produce colors when they absorb some wavelengths of light and transmit or reflect other wavelengths. You can use reflected light to explain why grass is green. You learned that in raindrops and prisms, different wavelengths of light are bent through different angles—resulting in rainbows and spectrums.

However, the shining colors you see in a peacock's tail feathers, mother-of-pearl shells, soap bubbles, and the swirling colors on oil-covered puddles have a different origin. These colors are a result of interference—the way light rays combine together in thin films of matter.

There is yet another way colors form. Light waves follow a specific behavior as they bend around the edges of an object. This behavior, called diffraction, is responsible for the brilliant iridescent colors you see on the backs of some beetles and glancing off compact disks.

Using their observations of the behavior of light in nature, scientists have developed instruments that can accurately measure the wavelengths of specific light waves. If you have examined microorganisms or other extremely small objects through optical microscopes, the sharp images you saw are the result of understanding and applying the principles governing light's behavior. So far there is only one barrier to viewing very small objects with an optical microscope: the object being examined must be no smaller than the wavelength of the light waves used to examine it.

In this chapter, you will learn about interference and diffraction of light. You will also learn what part a wave's length plays in these two phenomena.

WHAT YOU'LL LEARN

- You will define diffraction and relate it to the interference of light waves.
- You will describe the operation of a grating spectrometer.

WHY IT'S IMPORTANT

- By understanding diffraction, you can identify the resolving powers of microscopes and telescopes.
- It is possible to measure wavelengths of light accurately with a grating spectrometer.

PHYSICS
Online

To find out more about diffraction and interference of light, visit the Glencoe Science Web site at **science.glencoe.com**

CLICK HERE

19.1 When Light Waves Interfere

Sir Isaac Newton, whose laws of motion you studied in Chapter 5, believed that light was composed of fast-moving, unimaginably tiny particles, which he called corpuscles. He was aware that the Italian scientist Francesco Maria Grimaldi (1618–1663) had observed that the edges of shadows are not perfectly sharp. But Newton thought that Grimaldi's result was caused by the interaction of light corpuscles with the vibrating particles on the edges of openings. Newton probably never imagined that the wavelengths of visible light might be so tiny they could produce such small diffraction effects.

OBJECTIVES

- **Relate** the diffraction of light to its wave characteristics.

- **Explain** how light falling on two closely spaced slits produces an interference pattern, and use measurements to **calculate** wavelengths of light.

- **Apply** geometrical models to **explain** single-slit diffraction and two-slit interference patterns.

Diffraction

Grimaldi named the slight spreading of light around barriers diffraction. The Dutch scientist Christiaan Huygens (1629–1695) proposed a wave model to explain diffraction. According to Huygens, all the points of a wave front of light could be thought of as new sources of smaller waves. These wavelets expand in every direction and are in step with one another. A light source consists of an infinite number of point sources, which generate a plane wave front, as shown in **Figure 19–1.**

Much later, the English physician Thomas Young (1773–1829) read Newton's book on optics while studying the human eye. He became convinced that Newton's descriptions of light behavior in optics could be explained if light were a wave with an extremely small wavelength. In 1801, Young developed an experiment that allowed him to make a precise measurement of light's wavelength using diffraction.

Young's two-slit experiment Young's experiment not only enabled him to measure light's wavelength, but also provided additional evidence of the wave nature of light. Young directed a beam of light at two closely spaced narrow slits in a barrier. The light was diffracted, and the rays from the two slits overlapped. When the overlapping light beams from the two slits fell on an observing screen on the other side of the

FIGURE 19–1 According to Huygens, the crest of each wave can be thought of as a series of point sources. Each point source creates a circular wavelet. All the wavelets add together. In the center of the beam, the wave front is flat, but at the edges the circular waves spread out. The beam no longer has sharp edges.

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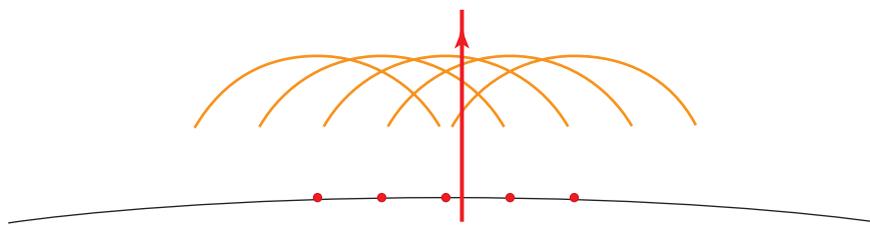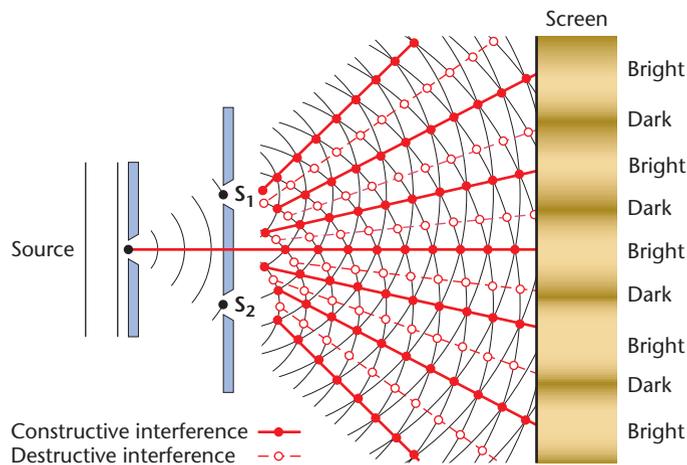
FIGURE 19–2 The diffraction of monochromatic light through a double slit produces bright and dark bands on a screen.

barrier, the overlap did not produce extra light, but a pattern of bright and dark bands, which Young called **interference fringes.** He explained that these bands must be the result of constructive and destructive interference of the light waves from the two slits.

Young placed a narrow slit in front of a **monochromatic light** source, one that emits light of only one wavelength. Only a small part of the light from the source passed through the slit, ensuring that the waves were in phase; that is, the waves' crests reached the same point at the same time—as did their troughs. Waves of this type are called **coherent waves.**

The waves spread out after passing through the single slit and fell on the double slit. The waves were again diffracted at the double slit, which acted as two sources of new circular waves spreading out on the far side of this second barrier, as shown in **Figure 19–2.** The semicircles represent wave crests moving outward from the slits. Midway between the crests are the troughs. At the points where the two crests overlap, the waves interfere constructively, and the light intensity increases creating a bright band on a screen. Where a crest and a trough meet, they interfere destructively, canceling each other out and creating a dark region.

Diffraction of white light In a diffraction experiment that uses monochromatic light, constructive interference produces a bright central band on the screen, as well as other bright bands on either side, **Figure 19–3a** and **b.** Between the bright bands are dark areas located where destructive interference occurs. However, when white light is used in a double-slit experiment, diffraction causes the appearance of colored spectra instead of bright and dark bands, as shown in **Figure 19–3c.** 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.

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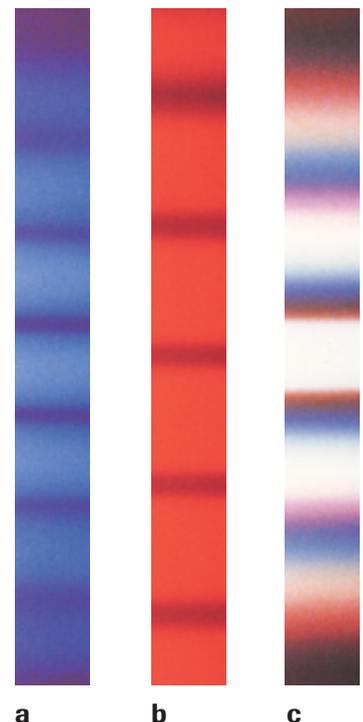
FIGURE 19–3 The diffraction of a monochromatic light source produces interference on the screen resulting in a pattern, such as the one shown for blue light **(a)** and for red light **(b).** The diffraction of white light produces bands of different colors **(c).**

Wavelengths of Colors

Problem

How can you accurately measure the wavelength of four colors of light?

Diffraction grating

Index card strip

Clay

x 90°

$L = 1.0$ m

Materials

meterstick
index card
40-W straight filament light
ball of clay
tape
diffraction grating
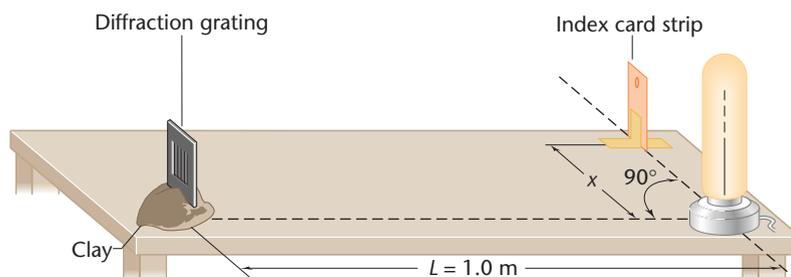
Procedure

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.

3. Place the ball of clay 1.0 m on the bench 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 bands of 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 stand behind the lamp and move the strip labeled "O" from side to side until you see it in place with the middle of its color. Ask your partner to tape the strip to the table at that point.

7. Repeat step 6 for each of the other colored strips.

8. When you are completely finished with the lab dispose of or recycle appropriate materials. Put away materials that can be reused.

Data and Observations				
Color	x	d	L	λ

Analyze and Conclude

1. Observing and Inferring What color is closest to the lamp? Suggest a reason and list the order that colors occur, beginning from red.

2. Making and Using a Table Make a data table like the one shown or a spreadsheet to record x, d, and L for each of the four colors. Measure and record x for each strip to the nearest 0.1 cm. Record the value of d provided by your teacher.

3. Calculating Use equation $\lambda = xd/L$ to calculate the wavelength for each color, and record this value in nanometers in your data table or spreadsheet.

Apply

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

2. Suppose your diffraction grating had more grooves/centimeter. How would this change the diffraction pattern you see?

CONTENTS

Measuring the Wavelength of a Light Wave

Young used the double-slit experiment to make the first precise measurement of the wavelength of light. A diagram of this experiment is shown in **Figure 19–4,** which is not drawn to scale so that all points can be observed. Regardless of the wavelength of light used, light reaching point P_0 travels the same distance from each slit. Therefore, all wavelengths of light interact constructively. 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, S_1 and S_2, interferes constructively. The two path lengths, which would be much larger in reality than is shown in the model, differ by one wavelength. That is, the distance PS_1 is one wavelength longer than PS_2.

To measure wavelength, Young first measured the distance between P_0 and P, labeled x in **Figure 19–4.** The distance between the screen and the slits is L, and the separation of the two slits is d. In the right triangle NS_1S_2, the side S_1N is the length difference of the two light paths. S_1N 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, OP nearly equals the distance L, and the lines NS_2 and OP are nearly perpendicular to each other. Because the triangle NS_1S_2 is similar to triangle PP_0O, the ratio of the corresponding sides of these similar triangles is the same, as shown by the following equation.

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

The equation to solve for λ is then given as follows.

Wavelength Using Double-Slit Interference $\quad \lambda = \dfrac{xd}{L}$

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 significant digits.

FIGURE 19–4 This diagram represents an analysis of the angles of light formed by double-slit interference. In reality, the distance, L, is about 10^5 times longer than the separation, d, between the two slits. It is necessary to distort the diagram so that the details close to the slit can be made clear.
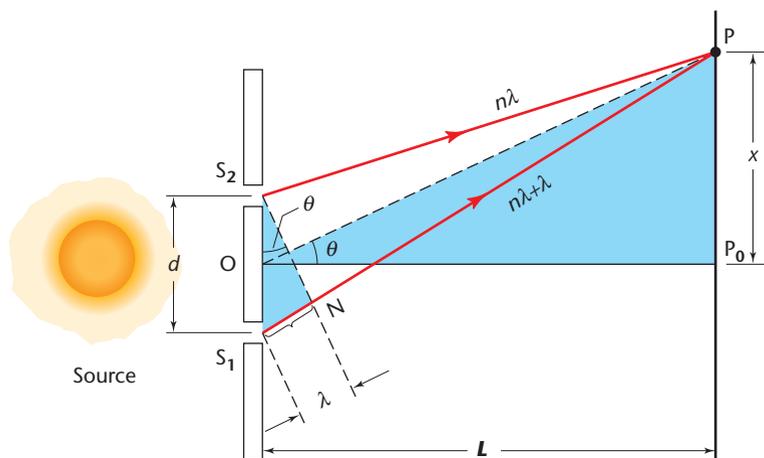
Pocket Lab

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.

Observing and Inferring Describe what you see. Which color appears first? What happens to the brightness of previous colors as new colors become visible? What is the order of the colors?

Wavelength of Light

A two-slit experiment is performed to measure the wavelength of red light. The slits are 0.0190 mm apart. A screen is placed 0.600 m away and the separation between the central bright line and the first-order bright line is found to be 21.1 mm. What is the wavelength of the red light?

Sketch the Problem

- Sketch the experiment.
- Label knowns and unknowns.

Calculate Your Answer

Known:	**Unknown:**
$d = 1.90 \times 10^{-5}$ m	$\lambda = ?$
$x = 2.11 \times 10^{-2}$ m	
$L = 0.600$ m	

Strategy:

Solve for the wavelength.

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

Calculations:

$$\lambda = \frac{(2.11 \times 10^{-2} \text{ m})(1.90 \times 10^{-5} \text{ m})}{0.600 \text{ m}}$$

$$= 668 \text{ nm}$$

Check Your Answer

- The answer is in m or nm, which are correct for wavelength.
- The wavelength of red light is near 700 nm; and that of blue is near 400 nm. So the answer is reasonable for red light.

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 aimed at two slits separated by 1.90×10^{-5} m. What is the distance from the central line to the first-order yellow line if the screen is 0.600 m from the slits?

3. In a double-slit experiment, physics students use a laser with a known wavelength of 632.8 nm. 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?

CONTENTS

FIGURE 19–5 This diffraction pattern for red light was produced with a single slit having a width of 0.02 cm.

Single-Slit Diffraction

Suppose that you walk by the open door of the band rehearsal room at school. You hear the music as you walk toward the rehearsal room door long before you can see the players through the door. Sound seems to have reached you by bending around the edge of the door, whereas the light, which enables you to see the band players, has traveled only in a straight line. Both sound and light are composed of waves, so why don't they seem to act the same? In fact, they do behave in the same way. As Grimaldi first noted, the spreading of waves, or diffraction, occurs in both cases, but, because of light's much smaller wavelengths, the diffraction is much less obvious.

From one to many slits When light passes through a single, small opening, light is diffracted, and a series of bright and dark bands appears. Instead of the equally spaced, bright bands you have seen produced by two slits, the pattern from a single slit has a wide, bright central band with dimmer bands on either side, as shown in **Figure 19–5.**

To understand single-slit diffraction, suppose that the single slit has a width w. Imagine the slit as being divided into a large number of even smaller slits of width dw. Just as in two-slit interference, a dark band is produced each time light passing through a pair of these smaller slits interferes destructively.

How can you choose pairs of tiny slits so that each pair has the same separation? Divide the single slit into two equal parts and choose one tiny slit from each part so that each pair will be separated by a distance $w/2$, as shown in **Figure 19–6a.** That is, for any tiny slit in the top half, there will be another tiny slit in the bottom half, a distance $w/2$ away.
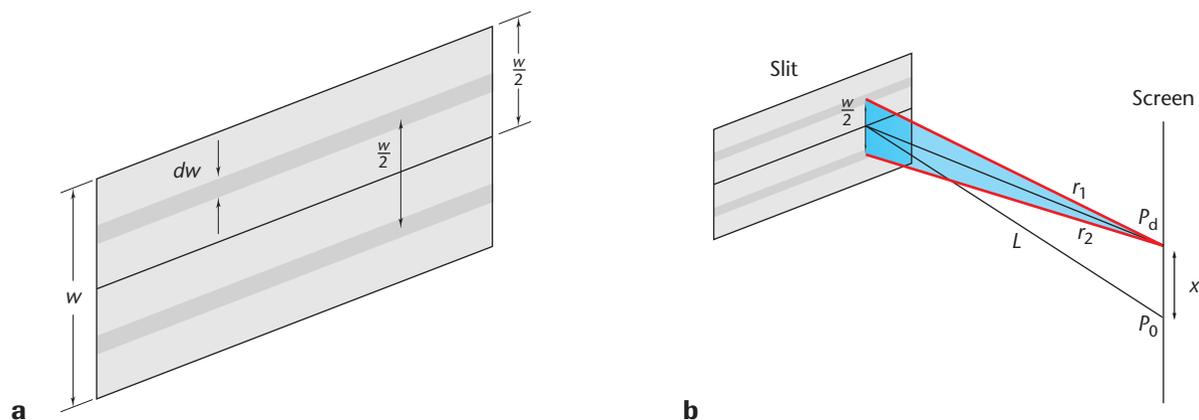
FIGURE 19–6 A slit of width w is divided into pairs of tiny slits, each separated by $w/2$ **(a).** Light passing through the slit forms a diffraction pattern on the screen **(b).** By studying this diffraction pattern, it is possible to determine the slit width, w, if L and the wavelength of the light, λ, are known.

a

b

CONTENTS

Measuring a wavelength of light If the slit is now illuminated, a central bright band appears at location P_0 on the screen, as shown in **Figure 19–6b.** But at position P_d, the path lengths r_2 and r_1 differ by one-half wavelength and produce a dark band. How far is the dark band from the central bright band? The situation is similar to that of double-slit interference, but the paths are now different by $\lambda/2$ and the separation between the slits is now $w/2$. The ratio of sides of the triangle can be shown in the following way.

$$\frac{x}{L} = \frac{\lambda/2}{w/2} = \frac{\lambda}{w}$$

The distance between the central bright band and the first dark band, x, can be determined by the following equation.

$$x = \frac{\lambda L}{w}$$

Additional dark bands occur where the path lengths differ by $3\lambda/2$, $5\lambda/2$, and so on. **Figure 19–7** shows examples of single-slit diffraction using different light sources.

It can be seen from this model that if you make the slit width smaller, you will make the bright band—that is, the distance between the dark bands—wider. If you use light with a longer wavelength, which is more toward the red end of the visible spectrum, you also increase the width of the bright band. Thus, the interference fringes that indicate the wave properties of light become noticeable when the light passes through small openings, which still are up to ten or 100 times the light's wavelength. Large openings, however, cast sharp shadows, as Newton first observed; thus, they do not as clearly reveal the wave nature of light.

a

b

c

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. Note that the red light has a longer wavelength than that for the blue light.

CONTENTS

4. A double-slit apparatus, $d = 15$ μm, is used to determine the wavelength of an unknown green light. The first-order line is 55.8 mm from the central line on a screen that is 1.6 m from the slits. What is the wavelength of the light?

5. Monochromatic green light of wavelength 546 nm falls on a single slit with 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 on which 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. Which filter produced the wider band?
   b. Calculate the width of the central bright band for each of the two filters.

19.1 Section Review

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. Describe how a wave behaves when it encounters a slit, and explain why some regions are bright and others are dark.

2. Sketch the pattern described in question 1.

3. Sketch what happens to the pattern in question 1 if the red light is replaced by blue light.

4. Research and describe Young's contributions to physics. Evaluate the impact of his research on the scientific thought of the nature of light.

5. **Critical Thinking** One of the slits in question 1 is covered so that no light can get through. What happens to the pattern?

Applications of Diffraction

The iridescent colors seen in many beetles are produced by diffraction. A beetle's hard back is covered with tiny ridges only a few hundred nanometers apart. Each space between the ridges acts as a slit and diffracts the light that hits it, thereby producing interference effects. The interference pattern from two slits is enhanced by this arrangement of many ridges and slits in series. In the same way, the spaces between the grooves on a compact disk diffract light and produce the familiar multicolored light reflected from a CD.

Diffraction Gratings

Although single-slit diffraction or two-slit interference can be used to measure the wavelength of light, diffraction gratings, such as those shown in **Figure 19–8,** are used in actual practice. A **diffraction grating** is a device that transmits or reflects light and forms an interference pattern in the same way that a double slit does. Diffraction gratings are made by scratching very fine lines with a diamond point on glass. The spaces between the scratched lines act like slits. Gratings can have as many as 10 000 lines per centimeter. That is, the spacing between the

OBJECTIVES

- **Explain** how diffraction gratings form interference patterns and how they are used in grating spectrometers.
- **Discuss** how diffraction limits the ability of a lens to distinguish two closely spaced objects.

On the Right Wavelength

➡ *Answers question from page 442.*

FIGURE 19–8 Diffraction gratings are used to create interference patterns for the analysis of light sources.

CONTENTS

How It Works

Holograms

Holography is a form of photography that produces a three-dimensional image. Because they are difficult to reproduce, holograms are often placed on credit cards to help in the prevention of counterfeiting. In some manufacturing industries, "before" and "after" holograms are used to evaluate the effects of stress on various materials.

1 A hologram is made by first passing a coherent beam of light onto a semitransparent mirror.

2 The mirror then splits the beam into two beams: the object beam and the reference beam.

3 The object beam passes through a lens and is reflected from a mirror to illuminate the object. The beam in turn reflects from the object onto a photographic film or plate.

4 The reference beam is first reflected from a mirror, then it is spread by a lens and is directed over the object beam on the film or plate.

5 The superimposed beams on the plate form an interference pattern that allows the plate to record both the intensity and relative phase of the light from each point on the object.

Coherent light source
Object beam
①
②
Lens
Mirror
Mirror
③
Object
Reference beam
④
Lens
Mirror
⑤
Photographic plate
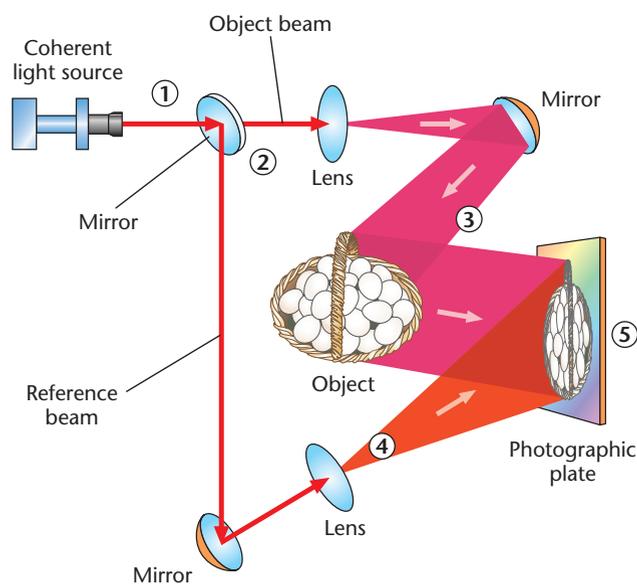
6 When the photographic film or plate is developed, the resulting picture of the interference pattern becomes a hologram of the object. When the hologram is illuminated, a hovering image containing rainbowlike bands of color is visible.

Thinking Critically

1. Why can't a hologram be produced using a fluorescent light source?

2. Find out what the term *parallax* means. How can this term be used to describe a hologram?

FIGURE 19–9 A spectroscope **(a)** is used to measure the wavelengths of light emitted by a light source **(b).**

The interference pattern produced by a diffraction grating has bright bands in the same locations caused by a double slit, but the bands are narrower and the dark regions are broader. As a result, individual colors can be distinguished more easily. Wavelengths can be measured more precisely with a diffraction grating than with double slits.

Earlier in this chapter, you used the following equation to calculate the wavelength of light using double-slit interference.

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

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 measure the angle θ, as indicated in **Figure 19–9.** Because x is so much smaller than L, the distance from the center of the slits to P, OP, is almost equal to the perpendicular distance L. Thus the ratio x/L can be replaced by $\sin \theta$. In equation form, this is shown as $\sin \theta \approx x/L$. Therefore, the wavelength can be found first by measuring the angle between

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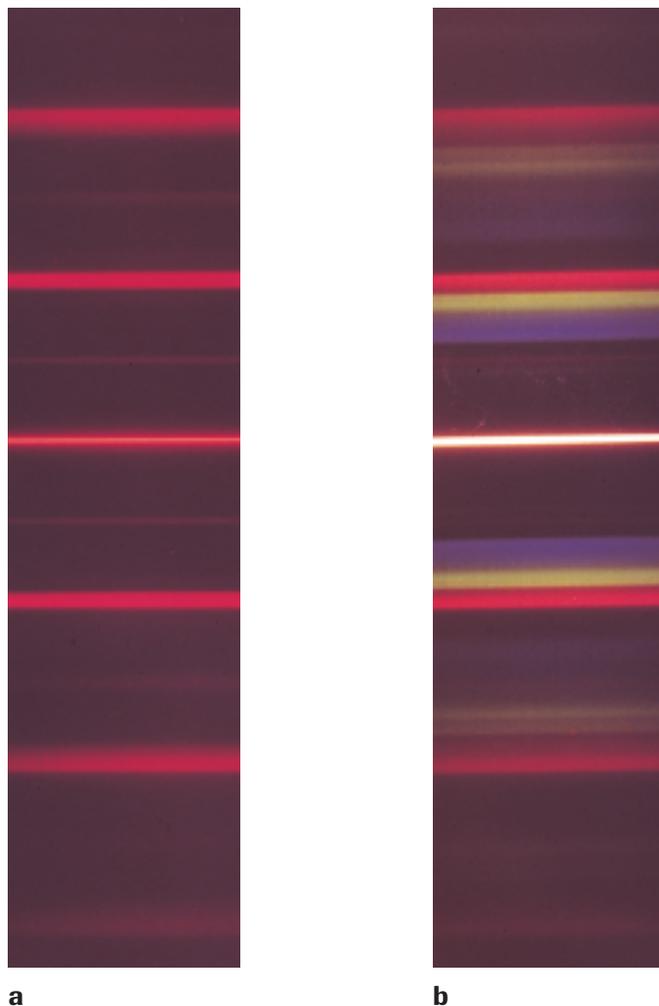
FIGURE 19–10 A grating was used to produce interference patterns for red light **(a)** and white light **(b).**

a   **b**

the central bright band and the first-order line, and then by using the following equation.

Wavelength Using a Diffraction Grating $\lambda = \dfrac{xd}{L} = d \sin \theta$

The instrument used to measure light wavelengths produced by a diffraction grating is called a grating spectroscope, shown in **Figure 19–9a.** As you look through a telescope from one end, the source at the other end emits light that falls on a slit and then passes through a diffraction grating, **Figure 19–9b.** When monochromatic red light is used, you will see a series of bright bands to either side of the central bright line, as shown in **Figure 19–10a.** When white light falls on the instrument, each red band is replaced by a spectrum, as shown in **Figure 19–10b.** The red band in the spectrum is at the same location on the screen as it is for a monochromatic light. The telescope can be 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.

Pocket Lab

Lights in the Night

Obtain small pieces of red and blue cellophane. When it is dark, find a long stretch of road and estimate the distance to cars when you can just barely tell that they have two headlights on. When a car is far away, its lights blend together. Look at these distant lights through the red cellophane and also through the blue cellophane. Which color makes it easier to resolve the two lights into separate images?

Determining Cause and Effect Explain why one color is more effective in separating the lights. Suggest how the use of blue filters might be useful for scientists working with telescopes or microscopes.

CONTENTS

Resolving Power of Lenses

When light enters 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 to be spread out. If two stars are close enough together, the images may be so blurred by diffraction that a viewer cannot tell whether there are two stars or only one.

Some telescopes are not powerful enough to resolve the blurred images of the two stars. Lord Rayleigh (1842–1919) established the **Rayleigh criterion** for resolution. If the central bright band of one star falls on the first dark band of the second, the two stars will be just resolved. That is, a viewer will be able to 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 limits the resolving power of microscopes as well as telescopes. 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 formed by red light. Thus, microscopes used by biologists often use blue or violet light to illuminate their objectives.

19.2 Section Review

1. Many narrow slits are close to each other and equally spaced 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 visible on the paper. Sketch the pattern that would be seen on the screen.

2. You shine a red laser light through one diffraction grating, forming a pattern of red dots on a screen. Then you substitute a second diffraction grating for the first one, forming a different pattern. The dots produced by one grating are spread more than those produced by the other. Which grating has more lines per millimeter?

3. An astronomer uses a telescope to view a number of closely spaced stars. Colored filters are available to select only certain colors from the starlight. Through which filter, red or blue, could the astronomer more easily count the stars? Explain.

4. Research and interpret the role of diffraction in medicine and astronomy.

5. **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?

Summary

Key Terms

19.1
- interference fringe
- monochromatic light
- coherent wave

19.2
- diffraction grating
- Rayleigh criterion

19.1 When Light Waves Interfere
- Light has wave properties.
- Light passing through two closely spaced, narrow slits produces a pattern of dark and light bands on a screen called an interference pattern.
- Interference patterns can be used to measure the wavelength of light.
- Light passing through a narrow hole or slit is diffracted, or spread from a straight-line path, and produces a diffraction pattern on a screen.
- Both interference and diffraction patterns depend on the wavelength of light, the width or separation of the slits, and the distance to the screen.
- Interference patterns are narrower and sharper than diffraction patterns.

19.2 Applications of Diffraction
- Diffraction gratings consist of large numbers of slits and produce narrow interference patterns.
- Diffraction gratings can be used to measure the wavelength of light precisely or to separate light composed of different wavelengths.
- Diffraction limits the ability of a lens to distinguish two closely spaced objects.

Key Equations

19.1 ....

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

19.2 ....

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

Reviewing Concepts

Section 19.1

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 the diffraction of sound waves more familiar in everyday experience than is the diffraction of light waves?
5. For each of the following examples, state whether the color is produced by diffraction, refraction, or the presence of pigments.

   a. soap bubbles
   b. rose petals
   c. mother of pearl
   d. oil films
   e. a rainbow

Section 19.2

6. As monochromatic light passes through a diffraction grating, what is the difference between the path lengths of light from two adjacent slits to a dark area on the screen?
7. When white light passes through a grating, what is visible on the screen? Why are no dark areas visible?
8. Why do diffraction gratings have large numbers of grooves? Why are these grooves so close together?

Chapter 19 Review **457**

9. Why would a telescope with a small diameter not be able to resolve the images of two closely spaced stars?

10. Why is blue light used for illumination in an optical microscope?

Applying Concepts

11. How can you tell whether an interference pattern is from a single slit or a double slit?

12. Describe the changes in a single-slit pattern as slit width is decreased.

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

14. What are the differences in the characteristics of the interference patterns formed by diffraction gratings containing 10^4 lines/cm and 10^5 lines/cm?

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

Problems

Section 19.1

16. Light falls on a pair of slits 19.0 μm apart and 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?

17. 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?

18. 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?

19. 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?

20. 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?

21. 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.

Section 19.2

22. A good diffraction grating has 2.5×10^3 lines per cm. What is the distance between two lines in the grating?

23. 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 first-order bright bands.

24. A camera with a 50-mm lens set at $f/8$ aperture has an opening 6.25 mm in diameter.
   a. 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 50.0 mm from the lens.
   b. The owner of a camera needs to decide which film to buy for it. The expensive one, called fine-grained film, has 200 grains/mm. The less costly, coarse-grained 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?

25. Suppose the Hubble Space Telescope, 2.4 m in diameter, is in orbit 100 km above Earth and is turned to look at Earth, as in **Figure 19–11.** If you ignore the effect of the atmosphere, what is the resolution of this telescope? Use $\lambda = 500$ nm.

FIGURE 19–11

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26. After passing through a 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?

27. Marie uses an old 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 visible.
   a. How many ridges are there in a centimeter along the radius of the record?
   b. Marie 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?

> **Extra Practice** **For more practice solving problems, go to Extra Practice Problems, Appendix B.**

Critical Thinking Problems

28. Yellow light falls on a diffraction grating. On a screen behind the grating you see three spots, one at zero degrees, where there is no diffraction, and one each at $+30°$ and $-30°$. You now add a blue light of equal intensity that is in the same direction as the yellow light. What pattern of spots will you now see on the screen?

29. Blue light of wavelength λ passes through a single-slit of width w. A diffraction pattern appears on a screen. If you now replace the blue light with a green light of wavelength 1.5λ, to what width should you change the slit in order to get the original pattern back?

30. At night, the pupil of a human eye can be considered to be a slit with a diameter of 8.0 mm. The diameter would be smaller in daylight. An automobile's headlights are separated by 1.8 m. How far away can the human eye distinguish the two headlights at night? **Hint:** Assume a wavelength of 500 nm and recall that Rayleigh's criterion stated that the peak of one image should be at the first minimum of the other.

Going Further

Team Project You and your team have been hired as consultants for a new sci-fi movie. The screenwriter is planning an attack by two groups of aliens. One group has eyes that can detect infrared wavelengths. The other has eyes sensitive to microwaves. The aliens can see (resolve) just as well as humans. The screenwriter asks you to decide whether or not this is reasonable.
   a. To determine the resolving power of humans, calculate the distance that a car is away from you so that you can still distinguish two headlights. **Hint:** Use yellow light to obtain λ, estimate the iris opening for humans, and estimate the separation of the car's headlights.
   b. Can you see a car's headlights at the distance calculated in **a?** Does diffraction limit your eyes' sensing ability? Hypothesize as to what might be the limiting factors.
   c. Determine the iris size for the alien that can detect the infrared wavelengths. Assume the same resolving ability as for humans and use a λ of 10 μm.
   d. Determine the iris size for the alien that can detect microwaves. Assume the same resolving ability as for humans and use a λ of 10 mm.
   e. Are the iris sizes of the two aliens reasonable? What would you tell the screenwriter concerning the design of his aliens?

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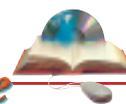
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