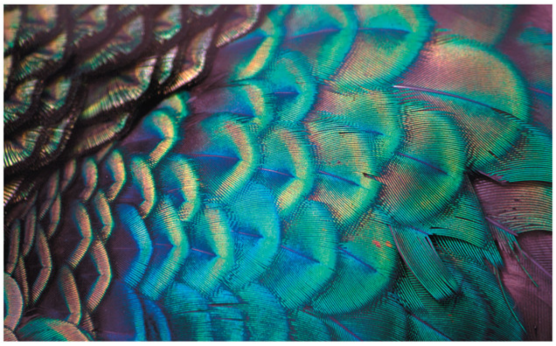
Chapter 22 Wave Optics



Chapter Goal: To understand and apply the wave model of light.

 Slide 22-2

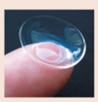
Chapter 22 Preview

Models of Light

You'll learn that light has aspects of both waves and particles. We'll introduce three models of light:

The **wave model** of light—the subject of this chapter—allows us to understand the colors of a soap bubble.

To understand the focusing of light by a contact lens, Chapter 23 will introduce a **ray model** in which light travels in particle-like straight lines.



Solar cells generate electricity from sunlight. The **photon model** of Part VII will be most appropriate for understanding this aspect of light.

 Slide 22-3

Chapter 22 Preview

Diffraction

Diffraction is the ability of waves to spread out after going through small holes or around corners. The diffraction of light indicates that light is a wave.

The "ripples" around the edges of this razor blade—back lit with a blue laser beam—are due to the diffraction of light.

 Slide 22-4

Chapter 22 Preview

Double-Slit Interference

You'll learn that an interference pattern is formed when light shines on an opaque screen with two narrow, closely spaced slits. This also shows that light is a wave.

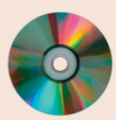
Interference fringes from green light passing through two closely spaced slits

Slide 22-5

Chapter 22 Preview

The Diffraction Grating

A **diffraction grating** is a periodic array of closely spaced holes or slits or grooves. You'll learn how a diffraction grating sends different wavelengths off at different angles.



The microscopic pits in this DVD act as a diffraction grating, breaking white light into its component colors.

Diffraction gratings are the basis for *spectroscopy*, an important tool for determining the composition of materials by the wavelengths they emit.

Slide 22-6

Chapter 22 Preview

Interferometry

Today, the controlled interference of light has applications that include optical computing, precision measurements in engineering, holography, and observing movements of the earth's crust.

Interference fringes such as these can be used to monitor vibrations and displacements of only a few nanometers.

Slide 22-7

Chapter 22 Reading Quiz

Reading Question 22.1

What was the first experiment to show that light is a wave?

A. Young's double-slit experiment.
B. Galileo's observation of Jupiter's moons.
C. The Michelson-Morley interferometer.
D. The Pound-Rebka experiment.
E. Millikan's oil-drop experiment.

Reading Question 22.2

What is a *diffraction grating*?

A. A device used to grate cheese and other materials.
B. A musical instrument used to direct sound.
C. An opaque screen with a tiny circular aperture.
D. An opaque screen with many closely spaced slits.
E. Diffraction gratings are not covered in Chapter 22.

Reading Question 22.3

When laser light shines on a screen after passing through two closely spaced slits, you see

A. A diffraction pattern.
B. Interference fringes.
C. Two dim, closely spaced points of light.
D. Constructive interference.

 Slide 22-13

Reading Question 22.4

This chapter discussed the

A. Acoustical interferometer.
B. Michelson interferometer.
C. Fabry-Perot interferometer.
D. Both A and B.
E. Both B and C.

 Slide 22-15

Reading Question 22.5

The spreading of waves behind an aperture is

A. More for long wavelengths, less for short wavelengths.
B. Less for long wavelengths, more for short wavelengths.
C. The same for long and short wavelengths.
D. Not discussed in this chapter.

 Slide 22-17

Reading Question 22.6

Apertures for which diffraction is studied in this chapter are

A. A single slit.
B. A circle.
C. A square.
D. Both A and B.
E. Both A and C.

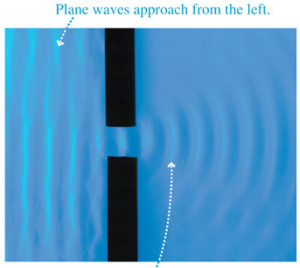
 Slide 22-19

Chapter 22 Content, Examples, and QuickCheck Questions

 Slide 22-21

Diffraction of Water Waves

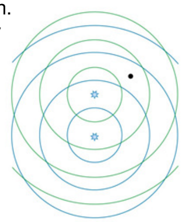
- A water wave, after passing through an opening, *spreads out* to fill the space behind the opening.
- This well-known spreading of waves is called **diffraction**.



 Slide 22-22

QuickCheck 22.1

Two rocks are simultaneously dropped into a pond, creating the ripples shown. The lines are the wave crests. As they overlap, the ripples interfere. At the point marked with a dot,

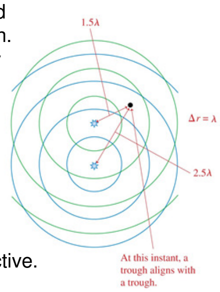


A. The interference is constructive.
B. The interference is destructive.
C. The interference is somewhere between constructive and destructive.
D. There's not enough information to tell about the interference.

 Slide 22-23

QuickCheck 22.1

Two rocks are simultaneously dropped into a pond, creating the ripples shown. The lines are the wave crests. As they overlap, the ripples interfere. At the point marked with a dot,

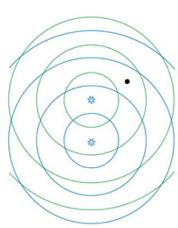


✔ **A. The interference is constructive.**
B. The interference is destructive.
C. The interference is somewhere between constructive and destructive.
D. There's not enough information to tell about the interference.

 Slide 22-24

QuickCheck 22.2

Two rocks are simultaneously dropped into a pond, creating the ripples shown. What would a person sitting at the dot observe over time?

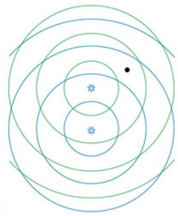


A. The water level would be consistently lower than in surrounding areas.
B. The water level would be consistently higher than in surrounding areas.
C. A large-amplitude water wave moving toward him or her.
D. A large-amplitude standing wave.
E. An extended period of flat water.

 Slide 22-25

QuickCheck 22.2

Two rocks are simultaneously dropped into a pond, creating the ripples shown. What would a person sitting at the dot observe over time?



A. The water level would be consistently lower than in surrounding areas.

B. The water level would be consistently higher than in surrounding areas.

✔ **C. A large-amplitude water wave moving toward him or her.**

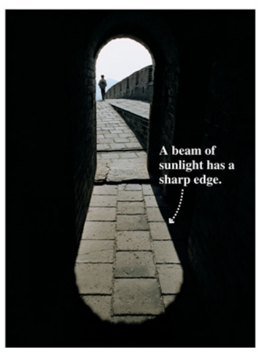
D. A large-amplitude standing wave.

E. An extended period of flat water.

 Slide 22-26

Models of Light

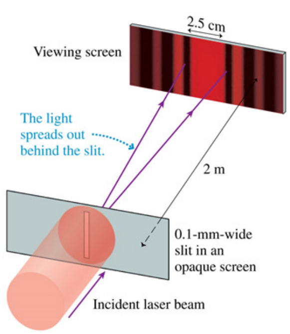
- Unlike a water wave, when light passes through a a large opening, it makes a sharp-edged shadow.
- This lack of noticeable diffraction means that if light is a wave, the wavelength must be very small.



 Slide 22-27

Diffraction of Light

- When red light passes through an opening that is only 0.1 mm wide, it does spread out.
- Diffraction of light is observable *if* the hole is sufficiently small.

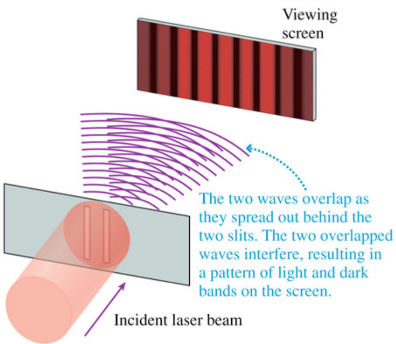


 Slide 22-28

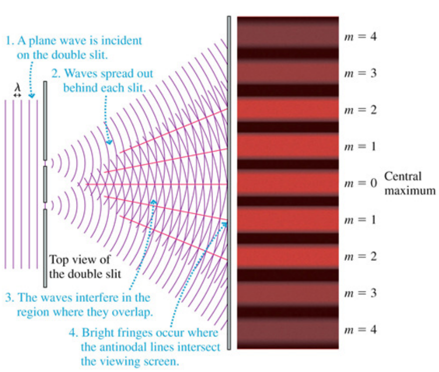
Models of Light

- **The wave model:** Under many circumstances, light exhibits the same behavior as sound or water waves. The study of light as a wave is called *wave optics***.**
- **The ray model:** The properties of prisms, mirrors, and lenses are best understood in terms of *light rays*. The ray model is the basis of *ray optics*.
- **The photon model:** In the quantum world, light behaves like neither a wave nor a particle. Instead, light consists of *photons* that have both wave-like and particle-like properties. This is the *quantum theory* of light.

Young's Double-Slit Experiment

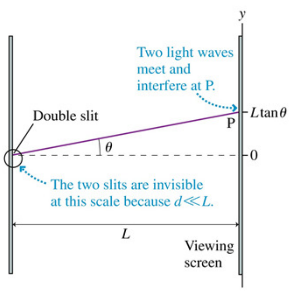


Young's Double-Slit Experiment



Analyzing Double-Slit Interference

- The figure shows the "big picture" of the double-slit experiment.
- The next slide *zooms in* on the area inside the circle.

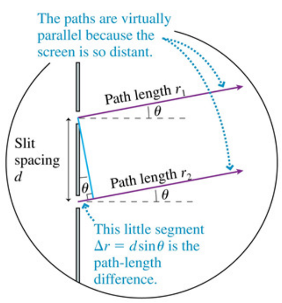


Analyzing Double-Slit Interference

- The figure shows a magnified portion of the double-slit experiment.
- The wave from the lower slit travels an extra distance.

$$\Delta r = d\sin\theta$$

- Bright fringes (constructive interference) will occur at angles θ_m such that $\Delta r = m\lambda$, where $m = 0, 1, 2, 3, \ldots$



Analyzing Double-Slit Interference

- The mth bright fringe emerging from the double slit is at an angle:

$$\theta_m = m\frac{\lambda}{d} \qquad m = 0, 1, 2, 3, \ldots \qquad \text{(angles of bright fringes)}$$

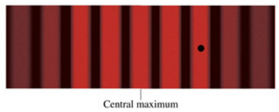
where θ_m is in radians, and we have used the small-angle approximation.

- The y-position on the screen of the mth bright fringe on a screen a distance L away is:

$$y_m = \frac{m\lambda L}{d} \qquad m = 0, 1, 2, 3, \ldots \qquad \text{(positions of bright fringes)}$$

QuickCheck 22.3

A laboratory experiment produces a double-slit interference pattern on a screen. The point on the screen marked with a dot is how much farther from the left slit than from the right slit?

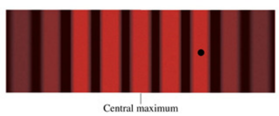


A. 1.0 λ.
B. 1.5 λ.
C. 2.0 λ.
D. 2.5 λ.
E. 3.0 λ.

Slide 22-35

QuickCheck 22.3

A laboratory experiment produces a double-slit interference pattern on a screen. The point on the screen marked with a dot is how much farther from the left slit than from the right slit?

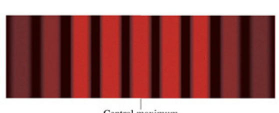


A. 1.0 λ.
B. 1.5 λ.
✔ **C. 2.0 λ.**
D. 2.5 λ.
E. 3.0 λ.

Slide 22-36

QuickCheck 22.4

A laboratory experiment produces a double-slit interference pattern on a screen. If the screen is moved farther away from the slits, the fringes will be

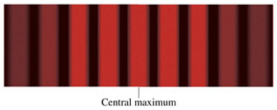


A. Closer together.
B. In the same positions.
C. Farther apart.
D. Fuzzy and out of focus.

Slide 22-37

QuickCheck 22.4

A laboratory experiment produces a double-slit interference pattern on a screen. If the screen is moved farther away from the slits, the fringes will be



A. Closer together.
B. In the same positions.
✔ **C. Farther apart.**
D. Fuzzy and out of focus.

 Slide 22-38

Example 22.1 Double-Slit Interference of a Laser Beam

EXAMPLE 22.1 Double-slit interference of a laser beam

Light from a helium-neon laser ($\lambda = 633$ nm) illuminates two slits spaced 0.40 mm apart. A viewing screen is 2.0 m behind the slits. What are the distances between the two $m = 2$ bright fringes and between the two $m = 2$ dark fringes?

MODEL Two closely spaced slits produce a double-slit interference pattern.

VISUALIZE The interference pattern is symmetrical, with $m = 2$ bright fringes at equal distances on both sides of the central maximum.

 Slide 22-39

Example 22.1 Double-Slit Interference of a Laser Beam

EXAMPLE 22.1 Double-slit interference of a laser beam

SOLVE The positions of the bright fringes are given by Equation 22.6. The $m = 2$ bright fringe is located at position

$$y_m = \frac{m\lambda L}{d} = \frac{2(633 \times 10^{-9}\text{ m})(2.0\text{ m})}{4.0 \times 10^{-4}\text{ m}} = 6.3\text{ mm}$$

Each of the $m = 2$ fringes is 6.3 mm from the central maximum; so the distance between the two $m = 2$ bright fringes is 12.6 mm. The $m = 2$ dark fringe is located at

$$y'_m = \left(m + \frac{1}{2}\right)\frac{\lambda L}{d} = 7.9\text{ mm}$$

Thus the distance between the two $m = 2$ dark fringes is 15.8 mm.

ASSESS Because the fringes are counted outward from the center, the $m = 2$ bright fringe occurs *before* the $m = 2$ dark fringe.

 Slide 22-40

Example 22.2 Measuring the Wavelength of Light

EXAMPLE 22.2 Measuring the wavelength of light

A double-slit interference pattern is observed on a screen 1.0 m behind two slits spaced 0.30 mm apart. Ten bright fringes span a distance of 1.7 cm. What is the wavelength of the light?

MODEL It is not always obvious which fringe is the central maximum. Slight imperfections in the slits can make the interference fringe pattern less than ideal. However, you do not need to identify the $m = 0$ fringe because you can make use of the fact that the fringe spacing Δy is uniform. Ten bright fringes have *nine* spaces between them (not ten—be careful!).

Slide 22-41

Example 22.2 Measuring the Wavelength of Light

EXAMPLE 22.2 Measuring the wavelength of light

SOLVE The fringe spacing is

$$\Delta y = \frac{1.7\text{ cm}}{9} = 1.89 \times 10^{-3}\text{ m}$$

Using this fringe spacing in Equation 22.7, we find that the wavelength is

$$\lambda = \frac{d}{L}\Delta y = 5.7 \times 10^{-7}\text{ m} = 570\text{ nm}$$

It is customary to express the wavelengths of visible light in nanometers. Be sure to do this as you solve problems.

Slide 22-42

Example 22.2 Measuring the Wavelength of Light

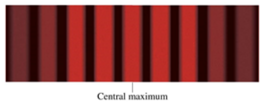
EXAMPLE 22.2 Measuring the wavelength of light

ASSESS Young's double-slit experiment not only demonstrated that light is a wave, it provided a means for measuring the wavelength. You learned in Chapter 20 that the wavelengths of visible light span the range 400–700 nm. These lengths are smaller than we can easily comprehend. A wavelength of 570 nm, which is in the middle of the visible spectrum, is only about 1% of the diameter of a human hair.

Slide 22-43

QuickCheck 22.5

A laboratory experiment produces a double-slit interference pattern on a screen. If green light is used, with everything else the same, the bright fringes will be

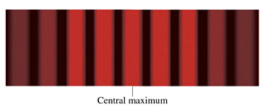


A. Closer together
B. In the same positions.
C. Farther apart.
D. There will be no fringes because the conditions for interference won't be satisfied.

Slide 22-44

QuickCheck 22.5

A laboratory experiment produces a double-slit interference pattern on a screen. If green light is used, with everything else the same, the bright fringes will be



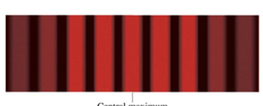
✔**A. Closer together.**
B. In the same positions.
C. Farther apart.
D. There will be no fringes because the conditions for interference won't be satisfied.

$\Delta y = \frac{\lambda L}{d}$ and green light has a shorter wavelength.

Slide 22-45

QuickCheck 22.6

A laboratory experiment produces a double-slit interference pattern on a screen. If the slits are moved closer together, the bright fringes will be

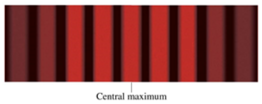


A. Closer together.
B. In the same positions.
C. Farther apart.
D. There will be no fringes because the conditions for interference won't be satisfied.

Slide 22-46

QuickCheck 22.6

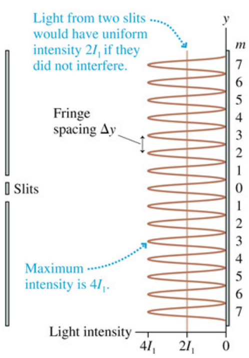
A laboratory experiment produces a double-slit interference pattern on a screen. If the slits are moved closer together, the bright fringes will be



A. Closer together.
B. In the same positions.
✔**C. Farther apart.**
D. There will be no fringes because the conditions for interference won't be satisfied.

$\Delta y = \frac{\lambda L}{d}$ and d is smaller.

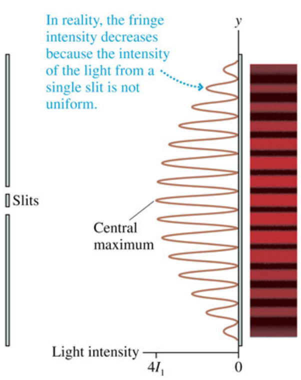
Intensity of the Double-Slit Interference Pattern



The intensity of the double-slit interference pattern at position y is:

$$I_{\text{double}} = 4I_1 \cos^2\left(\frac{\pi d}{\lambda L} y\right)$$

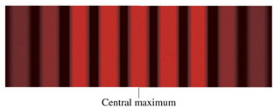
Intensity of the Double-Slit Interference Pattern



The actual intensity from a double-slit experiment slowly decreases as $|y|$ increases.

QuickCheck 22.7

A laboratory experiment produces a double-slit interference pattern on a screen. If the amplitude of the light wave is doubled, the intensity of the central maximum will increase by a factor of

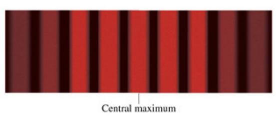


A. $\sqrt{2}$.
B. 2.
C. 4.
D. 8.

Slide 22-50

QuickCheck 22.7

A laboratory experiment produces a double-slit interference pattern on a screen. If the amplitude of the light wave is doubled, the intensity of the central maximum will increase by a factor of



A. $\sqrt{2}$.
B. 2.
✔**C. 4.**
D. 8.

Slide 22-51

The Diffraction Grating

- Suppose we were to replace the double slit with an opaque screen that has N closely spaced slits.
- When illuminated from one side, each of these slits becomes the source of a light wave that diffracts, or spreads out, behind the slit.
- Such a multi-slit device is called a **diffraction grating**.
- Bright fringes will occur at angles θ_m, such that:

$$d \sin\theta_m = m\lambda \qquad m = 0, 1, 2, 3, \ldots$$

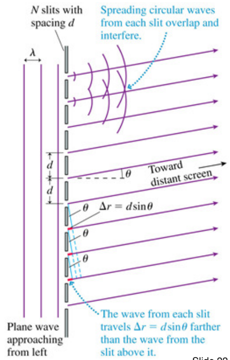
- The y-positions of these fringes will occur at:

$$y_m = L \tan\theta_m \qquad \text{(positions of bright fringes)}$$

Slide 22-52

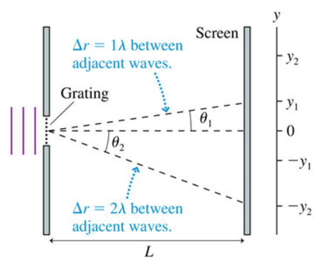
The Diffraction Grating

- The figure shows a diffraction grating in which N slits are equally spaced a distance d apart.
- This is a top view of the grating, as we look down on the experiment, and the slits extend above and below the page.
- Only 10 slits are shown here, but a practical grating will have hundreds or even thousands of slits.



 Slide 22-53

The Diffraction Grating



Bright fringes will occur at angles ϕ_m, such that

$$d \sin\phi_m = m\lambda$$

where $m = 0, 1, 2, 3, \ldots$

The y-positions of these fringes are:

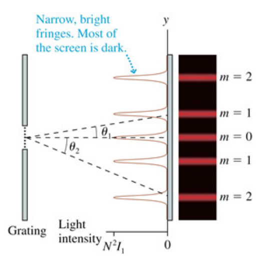
$$y_m = L \tan\theta_m \qquad \text{(positions of bright fringes)}$$

 Slide 22-54

The Diffraction Grating

- The integer m is called the **order** of the diffraction.
- The wave amplitude at the points of constructive interference is Na.
- Because intensity depends on the square of the amplitude, the intensities of the bright fringes are:

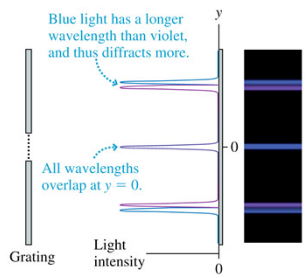
$$I_{max} = N^2 I_1$$



 Slide 22-55

The Diffraction Grating

- Diffraction gratings are used for measuring the wavelengths of light.
- If the incident light consists of two slightly different wavelengths, each wavelength will be diffracted at a slightly different angle.



Slide 22-56

QuickCheck 22.8

In a laboratory experiment, a diffraction grating produces an interference pattern on a screen. If the number of slits in the grating is increased, with everything else (including the slit spacing) the same, then

A. The fringes stay the same brightness and get closer together.
B. The fringes stay the same brightness and get farther apart.
C. The fringes stay in the same positions but get brighter and narrower.
D. The fringes stay in the same positions but get dimmer and wider.
E. The fringes get brighter, narrower, and closer together.

Slide 22-57

QuickCheck 22.8

In a laboratory experiment, a diffraction grating produces an interference pattern on a screen. If the number of slits in the grating is increased, with everything else (including the slit spacing) the same, then

A. The fringes stay the same brightness and get closer together.
B. The fringes stay the same brightness and get farther apart.
✔ **C. The fringes stay in the same positions but get brighter and narrower.**
D. The fringes stay in the same positions but get dimmer and wider.
E. The fringes get brighter, narrower, and closer together.

Slide 22-58

Example 22.3 Measuring Wavelengths Emitted by Sodium Atoms

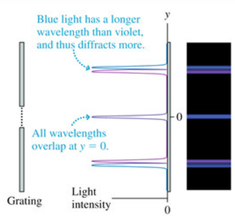
EXAMPLE 22.3 Measuring wavelengths emitted by sodium atoms

Light from a sodium lamp passes through a diffraction grating having 1000 slits per millimeter. The interference pattern is viewed on a screen 1.000 m behind the grating. Two bright yellow fringes are visible 72.88 cm and 73.00 cm from the central maximum. What are the wavelengths of these two fringes?

Example 22.3 Measuring Wavelengths Emitted by Sodium Atoms

EXAMPLE 22.3 Measuring wavelengths emitted by sodium atoms

VISUALIZE This is the situation shown in the figure. The two fringes are very close together, so we expect the wavelengths to be only slightly different. No other yellow fringes are mentioned, so we will assume these two fringes are the first-order diffraction ($m = 1$).



Example 22.3 Measuring Wavelengths Emitted by Sodium Atoms

EXAMPLE 22.3 Measuring wavelengths emitted by sodium atoms

SOLVE The distance y_m of a bright fringe from the central maximum is related to the diffraction angle by $y_m = L\tan\theta_m$. Thus the diffraction angles of these two fringes are

$$\theta_1 = \tan^{-1}\left(\frac{y_1}{L}\right) = \begin{cases} 36.08^\circ & \text{fringe at 72.88 cm} \\ 36.13^\circ & \text{fringe at 73.00 cm} \end{cases}$$

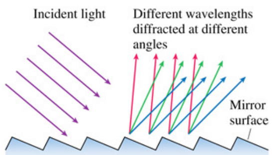
These angles must satisfy the interference condition $d\sin\theta_1 = \lambda$, so the wavelengths are $\lambda = d\sin\theta_1$. What is d? If a 1 mm length of the grating has 1000 slits, then the spacing from one slit to the next must be 1/1000 mm, or $d = 1.000 \times 10^{-6}$ m. Thus the wavelengths creating the two bright fringes are

$$\lambda = d\sin\theta_1 = \begin{cases} 589.0\ \text{nm} & \text{fringe at 72.88 cm} \\ 589.6\ \text{nm} & \text{fringe at 73.00 cm} \end{cases}$$

ASSESS We had data accurate to four significant figures, and all four were necessary to distinguish the two wavelengths.

Reflection Gratings

- In practice, most diffraction gratings are manufactured as *reflection gratings.*
- The interference pattern is exactly the same as the interference pattern of light transmitted through N parallel slits.

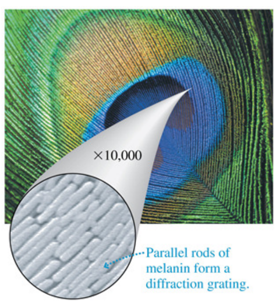


A reflection grating can be made by cutting parallel grooves in a mirror surface. These can be very precise, for scientific use, or mass produced in plastic.

Slide 22-62

Reflection Gratings

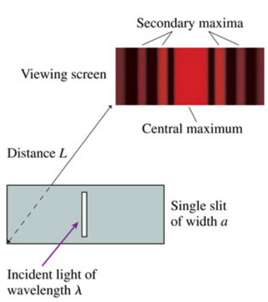
- Naturally occurring reflection gratings are responsible for some forms of color in nature.
- A peacock feather consists of nearly parallel rods of melanin, which act as a reflection grating.



Parallel rods of melanin form a diffraction grating.

Slide 22-63

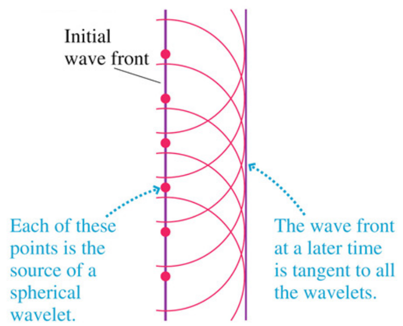
Single-Slit Diffraction



- Diffraction through a tall, narrow slit is known as single-slit diffraction.
- A viewing screen is placed distance L behind the slit of width a, and we will assume that $L >> a$.

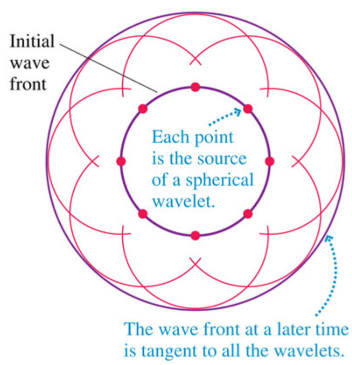
Slide 22-64

Huygens' Principle: Plane Waves



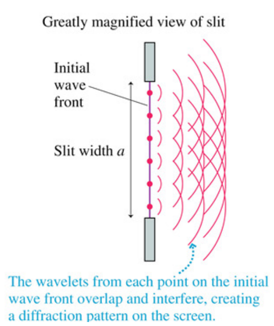
 Slide 22-65

Huygens' Principle: Spherical Waves



 Slide 22-66

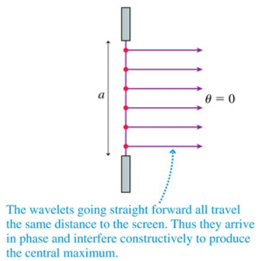
Analyzing Single-Slit Diffraction



- The figure shows a wave front passing through a narrow slit of width a.
- According to Huygens' principle, each point on the wave front can be thought of as the source of a spherical wavelet.

 Slide 22-67

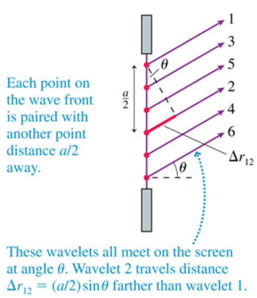
Analyzing Single-Slit Diffraction



- The figure shows the paths of several wavelets that travel straight ahead to the central point on the screen.
- The screen is *very* far to the right in this magnified view of the slit.
- The paths are very nearly parallel to each other, thus all the wavelets travel the same distance and arrive at the screen *in phase* with each other.

 Slide 22-68

Analyzing Single-Slit Diffraction

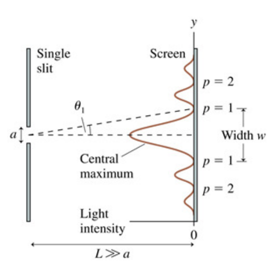


- In this figure, wavelets 1 and 2 start from points that are $a/2$ apart.
- Every point on the wave front can be paired with another point distance *a*/2 away.
- If the path-length difference is $\Delta r = \lambda/2$, the wavelets arrive at the screen out of phase and interfere destructively.

 Slide 22-69

Single-Slit Diffraction

- The light pattern from a single slit consists of a *central maximum* flanked by a series of weaker **secondary maxima** and dark fringes.
- The dark fringes occur at angles:



$$\theta_p = p\frac{\lambda}{a} \qquad p = 1, 2, 3, \ldots \qquad \text{(angles of dark fringes)}$$

 Slide 22-70

Example 22.4 Diffraction of a Laser Through a Slit

EXAMPLE 22.4 Diffraction of a laser through a slit

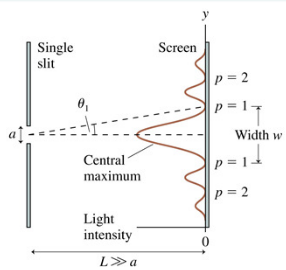
Light from a helium-neon laser ($\lambda = 633$ nm) passes through a narrow slit and is seen on a screen 2.0 m behind the slit. The first minimum in the diffraction pattern is 1.2 cm from the central maximum. How wide is the slit?

MODEL A narrow slit produces a single-slit diffraction pattern. A displacement of only 1.2 cm in a distance of 200 cm means that angle θ_1 is certainly a small angle.

Example 22.4 Diffraction of a Laser Through a Slit

EXAMPLE 22.4 Diffraction of a laser through a slit

VISUALIZE The intensity pattern will look like the figure below.



Example 22.4 Diffraction of a Laser Through a Slit

EXAMPLE 22.4 Diffraction of a laser through a slit

SOLVE We can use the small-angle approximation to find that the angle to the first minimum is

$$\theta_1 = \frac{1.2 \text{ cm}}{200 \text{ cm}} = 0.00600 \text{ rad} = 0.344°$$

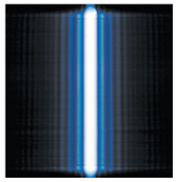
The first minimum is at angle $\theta_1 = \lambda/a$, from which we find that the slit width is

$$a = \frac{\lambda}{\theta_1} = \frac{633 \times 10^{-9} \text{ m}}{6.00 \times 10^{-3} \text{ rad}} = 1.1 \times 10^{-4} \text{ m} = 0.11 \text{ mm}$$

ASSESS This is typical of the slit widths used to observe single-slit diffraction. You can see that the small-angle approximation is well satisfied.

The Width of a Single-Slit Diffraction Pattern

- The central maximum of this single-slit diffraction pattern is much brighter than the secondary maximum.
- The width of the central maximum on a screen a distance L away is *twice* the spacing between the dark fringes on either side:



$$w = \frac{2\lambda L}{a} \qquad \text{(single slit)}$$

- The farther away from the screen (larger L), the wider the pattern of light becomes.
- The narrower the opening (smaller a), the wider the pattern of light becomes!

 Slide 22-74

QuickCheck 22.9

A laboratory experiment produces a single-slit diffraction pattern on a screen. If the slit is made narrower, the bright fringes will be

A. Closer together.
B. In the same positions.
C. Farther apart.
D. There will be no fringes because the conditions for diffraction won't be satisfied.

 Slide 22-75

QuickCheck 22.9

A laboratory experiment produces a single-slit diffraction pattern on a screen. If the slit is made narrower, the bright fringes will be

A. Closer together.
B. In the same positions.
✔**C. Farther apart.**
D. There will be no fringes because the conditions for diffraction won't be satisfied.

Minima between the bright fringes are at $y_p = \frac{p\lambda L}{a}$.

 Slide 22-76

Example 22.5 Determining the Wavelength

EXAMPLE 22.5 Determining the wavelength

Light passes through a 0.12-mm-wide slit and forms a diffraction pattern on a screen 1.00 m behind the slit. The width of the central maximum is 0.85 cm. What is the wavelength of the light?

SOLVE From Equation 22.22, the wavelength is

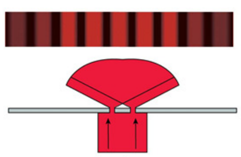
$$\lambda = \frac{aw}{2L} = \frac{(1.2 \times 10^{-4}\ \text{m})(0.0085\ \text{m})}{2(1.00\ \text{m})}$$

$$= 5.1 \times 10^{-7}\ \text{m} = 510\ \text{nm}$$

 Slide 22-77

QuickCheck 22.10

A laboratory experiment produces a double-slit interference pattern on a screen. If the left slit is blocked, the screen will look like



A. 

B. 

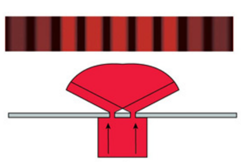
C. 

D. 

 Slide 22-78

QuickCheck 22.10

A laboratory experiment produces a double-slit interference pattern on a screen. If the left slit is blocked, the screen will look like



A. 

B. 

C. 

✔ **D.** 

 Slide 22-79

Circular-Aperture Diffraction

- Light of wavelength λ passes through a circular aperture of diameter *D*, and is then incident on a viewing screen a distance *L* behind the aperture, *L>>D.*
- The diffraction pattern has a circular central maximum, surrounded by a series of secondary bright fringes shaped like rings.
- The angle of the first minimum in the intensity is:

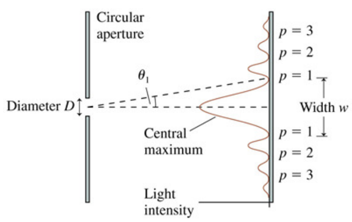
$$\theta_1 = \frac{1.22\lambda}{D}$$

- The width of the central maximum on the screen is:

$$w = 2y_1 = 2L\tan\theta_1 \approx \frac{2.44\lambda L}{D}$$

 Slide 22-80

The Diffraction of Light by a Circular Opening



 Slide 22-81

Example 22.6 Shining a Laser Through a Circular Hole

EXAMPLE 22.6 Shining a laser through a circular hole

Light from a helium-neon laser ($\lambda = 633$ nm) passes through a 0.50-mm-diameter hole. How far away should a viewing screen be placed to observe a diffraction pattern whose central maximum is 3.0 mm in diameter?

SOLVE Equation 22.24 gives us the appropriate screen distance:

$$L = \frac{wD}{2.44\lambda} = \frac{(3.0 \times 10^{-3}\text{ m})(5.0 \times 10^{-4}\text{ m})}{2.44(633 \times 10^{-9}\text{ m})} = 0.97\text{ m}$$

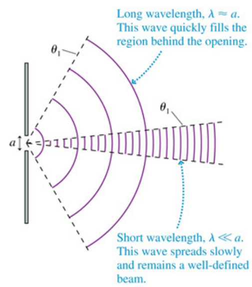
 Slide 22-82

The Wave and Ray Models of Light

- When light passes through an opening of size *a*, the angle of the first diffraction minimum is:

$$\theta_1 = \sin^{-1}\left(\frac{\lambda}{a}\right)$$

- Light waves, because of their very short wavelength, almost always have $\lambda/a << 1$ and diffract to produce a slowly spreading "beam" of light.



QuickCheck 22.11

A laboratory experiment produces a single-slit diffraction pattern on a screen. The slit width is a and the light wavelength is λ. In this case,

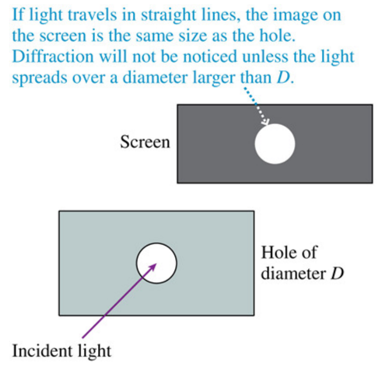
A. $\lambda < a$.
B. $\lambda = a$.
C. $\lambda > a$.
D. Not enough info to compare λ to a.

QuickCheck 22.11

A laboratory experiment produces a single-slit diffraction pattern on a screen. The slit width is a and the light wavelength is λ. In this case,

✔ **A. $\lambda < a$.**
B. $\lambda = a$.
C. $\lambda > a$.
D. Not enough info to compare λ to a.

The Wave and Ray Models of Light



Slide 22-86

The Wave and Ray Models of Light

- Light passes through a hole of diameter *D.*
- If the spreading due to diffraction is less than the size of the opening, use the ray model and think of light as traveling in straight lines.
- If the spreading due to diffraction is greater than the size of the opening, use the wave model of light.
- The crossover point between the two regimes occurs when the central-maximum width of a circular-aperture diffraction pattern is equal to the size of the opening:

$$\frac{2.44\lambda L}{D_c} = D_c$$

- For visible light with $\lambda \approx 500$ nm, and a typical laboratory distance of $L \approx 1$ m, $D_c \approx 1$ mm.

Slide 22-87

Tactics: Choosing a Model of Light

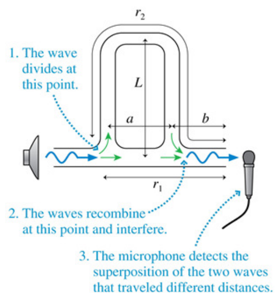
TACTICS BOX 22.1 **Choosing a model of light**

1. When visible light passes through openings smaller than about 1 mm in size, diffraction effects are usually important. Use the wave model of light.
2. When visible light passes through openings larger than about 1 mm in size, diffraction effects are usually not important. Use the ray model of light.

Slide 22-88

Interferometers

- The figure shows an *acoustical interferometer.*
- A sound wave is sent into the left end of the tube.
- Distance L can be changed by sliding the upper tube in and out like a trombone.
- Intensity of the emerging wave depends on L.



 Slide 22-89

Interferometers

- In an acoustic interferometer, the phase difference $\Delta\phi$ between the recombined waves is due entirely to the path-length difference between the waves, $\Delta r = r_2 - r_1 = 2L$.
- Constructive interference will occur when $\Delta r = m\lambda$ and destructive interference will occur when $\Delta r = (m + ½)\lambda$.
- The corresponding conditions on L are:

$$\text{Constructive:} \quad \Delta r = m\lambda \qquad m = 0, 1, 2, \ldots$$
$$\text{Destructive:} \quad \Delta r = \left(m + \frac{1}{2}\right)\lambda$$

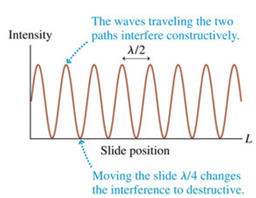
- The interferometer is used by recording the alternating maxima and minima in the sound as the top tube is pulled out and L changes.

 Slide 22-90

Interferometers

- The figure is a graph of the sound intensity at the microphone as L is increased.
- The number Δm of maxima appearing as the length changes by ΔL is:

$$\Delta m = \frac{\Delta L}{\lambda/2}$$



- This equation is the basis for measuring wavelengths very accurately.

 Slide 22-91

Example 22.7 Measuring the Wavelength of Sound

EXAMPLE 22.7 Measuring the wavelength of sound

A loudspeaker broadcasts a sound wave into an acoustical interferometer. The interferometer is adjusted so that the output sound intensity is a maximum, then the slide is slowly withdrawn. Exactly 10 new maxima appear as the slide moves 31.52 cm. What is the wavelength of the sound wave?

MODEL An interferometer produces a new maximum each time L increases by $\lambda/2$, causing the path-length difference Δr to increase by λ.

 Slide 22-92

Example 22.7 Measuring the Wavelength of Sound

EXAMPLE 22.7 Measuring the wavelength of sound

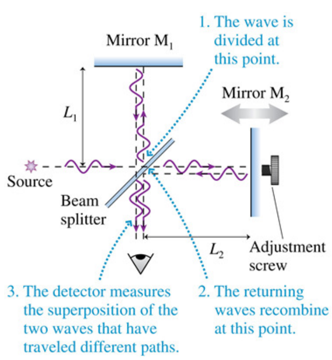
SOLVE Using Equation 22.30, we have

$$\lambda = \frac{2\Delta L}{\Delta m} = \frac{2(31.52\text{ cm})}{10} = 6.304\text{ cm}$$

ASSESS The wavelength can be determined to four significant figures because the distance was measured to four significant figures.

 Slide 22-93

The Michelson Interferometer



 Slide 22-94

The Michelson Interferometer

- In a Michelson interferometer, the phase difference $\Delta\phi$ between the recombined beams is due entirely to the path-length difference between the beams, $\Delta r = 2L_2 - 2L_1$.
- Constructive interference will occur when $\Delta r = m\lambda$.

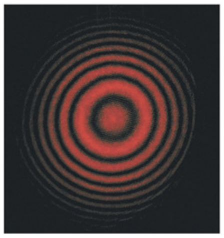
$$\text{Constructive:} \quad L_2 - L_1 = m\frac{\lambda}{2} \qquad m = 0, 1, 2, \ldots$$

- This equation is valid at the *center* of the beam; there is a bright central spot on the detector when this equation is true.

 Slide 22-95

The Michelson Interferometer

- The photograph shows the pattern of circular interference fringes seen in the output of a Michelson interferometer.
- If mirror M_2 is moved by turning the screw, the central spot in the fringe pattern alternates between bright and dark.



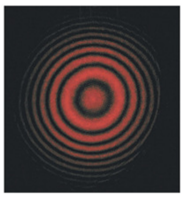
- The number Δm of maxima appearing as M_2 moves through a distance ΔL_2 is:

$$\Delta m = \frac{\Delta L_2}{\lambda/2}$$

 Slide 22-96

QuickCheck 22.12

A Michelson interferometer using red light with $\lambda = 650$ nm produces interference fringes with a bright spot at the center. If the light's wavelength is doubled to 1350 nm, with no other changes, the center (now detected with an infrared camera) will be

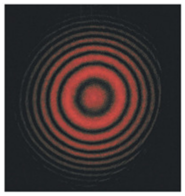


A. Bright.
B. Dark.
C. Somewhere between bright and dark.
D. Either bright or dark, but there's not enough information to say which.

 Slide 22-97

QuickCheck 22.12

A Michelson interferometer using red light with $\lambda = 650$ nm produces interference fringes with a bright spot at the center. If the light's wavelength is doubled to 1350 nm, with no other changes, the center (now detected with an infrared camera) will be



A. Bright.
B. Dark.
C. Somewhere between bright and dark.
✔ **D. Either bright or dark, but there's not enough information to say which.**

$\Delta r = 2\Delta L = m\lambda$

If λ is doubled, m must be halved to keep ΔL constant.

If m is even, $m/2$ is still an integer and the interference is still constructive.

If m is odd, $m/2$ is a half-integer and the interference is destructive.

 Slide 22-98

Example 22.8 Measuring the Wavelength of Light

EXAMPLE 22.8 Measuring the wavelength of light

An experimenter uses a Michelson interferometer to measure one of the wavelengths of light emitted by neon atoms. She slowly moves mirror M_2 until 10,000 new bright central spots have appeared. (In a modern experiment, a photodetector and computer would eliminate the possibility of experimenter error while counting.) She then measures that the mirror has moved a distance of 3.164 mm. What is the wavelength of the light?

MODEL An interferometer produces a new maximum each time L_2 increases by $\lambda/2$.

 Slide 22-99

Example 22.8 Measuring the Wavelength of Light

EXAMPLE 22.8 Measuring the wavelength of light

SOLVE The mirror moves $\Delta L_2 = 3.164 \text{ mm} = 3.164 \times 10^{-3}$ m. We can use Equation 22.33 to find

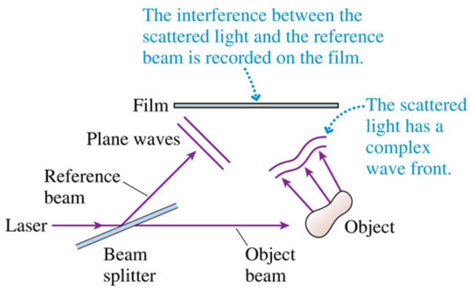
$$\lambda = \frac{2\Delta L_2}{\Delta m} = 6.328 \times 10^{-7} \text{ m} = 632.8 \text{ nm}$$

ASSESS A measurement of ΔL_2 accurate to four significant figures allowed us to determine λ to four significant figures. This happens to be the neon wavelength that is emitted as the laser beam in a helium-neon laser.

 Slide 22-100

Holography

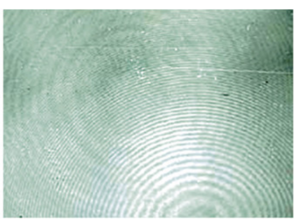
The figure shows shows how a **hologram** is recorded.



 Slide 22-101

Holography

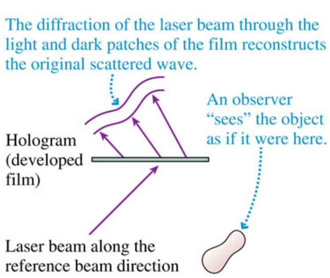
- Below is an enlarged photograph of a portion of a hologram.
- It's certainly not obvious that information is stored in this pattern, but it is.



 Slide 22-102

Holography

The hologram is "played" by sending just the reference beam through it.



 Slide 22-103

Holography

- The diffracted reference beam reconstructs the original scattered wave.
- As you look at this diffracted wave, from the far side of the hologram, you "see" the object exactly as if it were there.
- The view is three dimensional because, by moving your head with respect to the hologram, you can see different portions of the wave front.

Slide 22-104

Chapter 22 Summary Slides

Slide 22-105

General Principles

Huygens' principle says that each point on a wave front is the source of a spherical wavelet. The wave front at a later time is tangent to all the wavelets.

Slide 22-106

General Principles

Diffraction is the spreading of a wave after it passes through an opening.

Constructive and destructive interference are due to the overlap of two or more waves as they spread behind openings.

Slide 22-107

Important Concepts

The wave model of light considers light to be a wave propagating through space. Diffraction and interference are important.

The ray model of light considers light to travel in straight lines like little particles. Diffraction and interference are not important.

Diffraction is important when the width of the diffraction pattern of an aperture equals or exceeds the size of the aperture.
For a circular aperture, the crossover between the ray and wave models occurs for an opening of diameter $D_c \approx \sqrt{2\lambda L}$.

In practice, $D_c \approx 1$ mm for visible light. Thus

- Use the wave model when light passes through openings < 1 mm in size. Diffraction effects are usually important.
- Use the ray model when light passes through openings > 1 mm in size. Diffraction is usually not important.

Slide 22-108