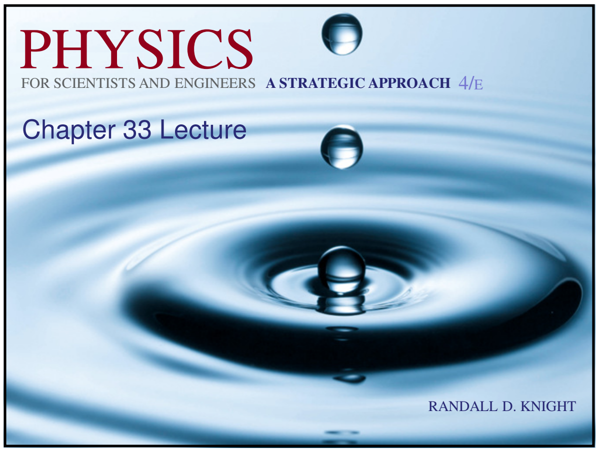
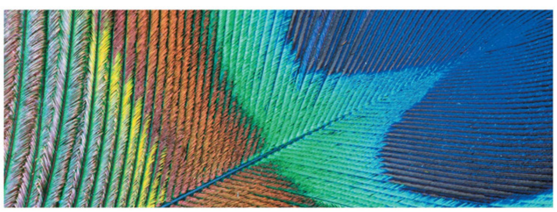


Chapter 33 Wave Optics



IN THIS CHAPTER, you will learn about and apply the wave model of light.

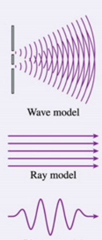
 Slide 32-2

Chapter 33 Preview

What is light?

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

- The wave model of light—the subject of this chapter—describes how light waves spread out and how the superposition of multiple light waves causes interference.
- The ray model of light, in which light travels in straight lines, will explain how mirrors and lenses work. It is the subject of Chapter 34.
- The photon model of light, which will be discussed in Part VIII, is an important part of quantum physics.



One of our tasks will be to learn when each model is appropriate.

« LOOKING BACK Sections 16.5, 16.7, and 16.8 Light waves, wave fronts, phase, and intensity

 Slide 32-3

Chapter 33 Preview

What is diffraction?

Diffraction is the ability of a wave to spread out after passing through a small hole or going around a corner. The diffraction of light indicates that light is a wave. One interesting finding will be that a *smaller* hole causes *more* spreading.

Slide 32-4

Chapter 33 Preview

Does light exhibit interference?

Yes. You previously studied the thin-film interference of light reflecting from two surfaces. In this chapter we will examine the interference fringes that are seen after light passes through two narrow, closely spaced slits in an opaque screen.

Double-slit interference

« LOOKING BACK Section 17.7 Interference

Slide 32-5

Chapter 33 Preview

What is a diffraction grating?

A diffraction grating is a periodic array of closely spaced slits or grooves. Different wavelengths are sent in different directions when light passes through a diffraction grating. Two similar wavelengths can be distinguished because the fringes of each are very narrow and precisely located.

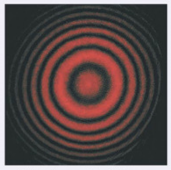
Diffraction-grating fringes

Slide 32-6

Chapter 33 Preview

How is interference used?

Diffraction gratings are the basis of spectroscopy, a tool for analyzing the composition of materials by the wavelengths they emit. Interferometers make precise measurements, ranging from the vibrations of wings to the movements of continents, with the controlled use of interference. And interference plays a key role in optical computers.



Interferometer fringes

Slide 32-7

Chapter 33 Reading Questions

Slide 32-8

Reading Question 33.1

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

Slide 32-9

Reading Question 33.1

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

Slide 32-10

Reading Question 33.2

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 33.

Slide 32-11

Reading Question 33.2

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 33.

Slide 32-12

Reading Question 33.3

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.

Reading Question 33.3

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.

Reading Question 33.4

This chapter discussed the

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

Reading Question 33.4

This chapter discussed the

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

Reading Question 33.5

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.

Reading Question 33.5

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.

Reading Question 33.6

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 32-19

Reading Question 33.6

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.

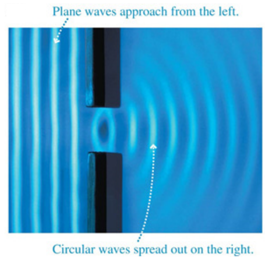
Slide 32-20

Chapter 33 Content, Examples, and QuickCheck Questions

Slide 32-21

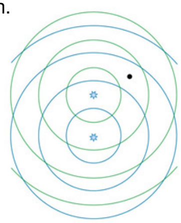
Diffraction of Water Waves

- 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**.



QuickCheck 33.1

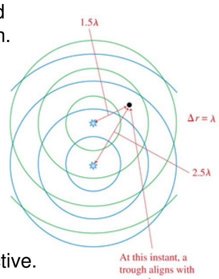
Two rocks are simultaneously dropped into a pond, creating the ripples shown. The lines are the wave crests. As they overlap, the ripples interfere. At the point marked with a dot,



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.

QuickCheck 33.1

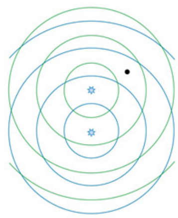
Two rocks are simultaneously dropped into a pond, creating the ripples shown. The lines are the wave crests. As they overlap, the ripples interfere. At the point marked with a dot,



✔ **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.

QuickCheck 33.2

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

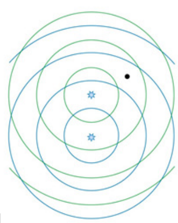


A. The water level would be consistently lower than in surrounding areas.
B. The water level would be consistently higher than in surrounding areas.
C. A large-amplitude water wave moving toward him or her
D. A large-amplitude standing wave
E. An extended period of flat water

Slide 32-25

QuickCheck 33.2

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 32-26

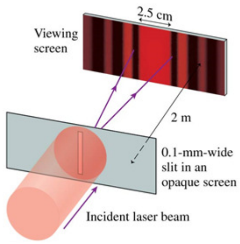
Models of Light

- 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 32-27

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.



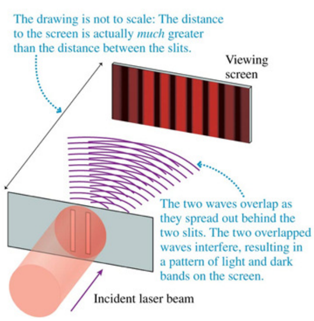
 Slide 32-28

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.

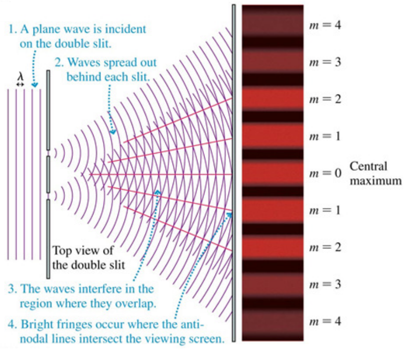
 Slide 32-29

Young's Double-Slit Experiment



 Slide 32-30

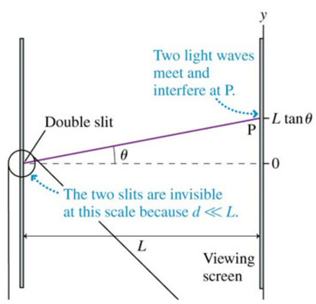
Young's Double-Slit Experiment



 Slide 32-31

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.



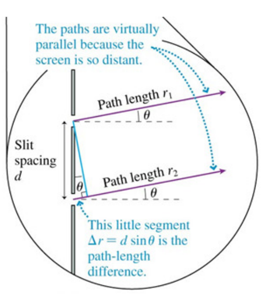
 Slide 32-32

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



 Slide 32-33

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.

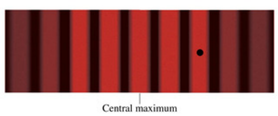
- The y-position on the screen of the mth bright fringe on a screen a distance L away is

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

Slide 32-34

QuickCheck 33.3

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?

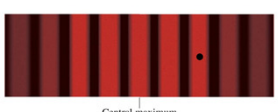


A. $1.0\,\lambda$
B. $1.5\,\lambda$
C. $2.0\,\lambda$
D. $2.5\,\lambda$
E. $3.0\,\lambda$

Slide 32-35

QuickCheck 33.3

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?

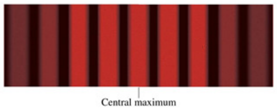


A. $1.0\,\lambda$
B. $1.5\,\lambda$
✔ **C. $2.0\,\lambda$**
D. $2.5\,\lambda$
E. $3.0\,\lambda$

Slide 32-36

QuickCheck 33.4

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

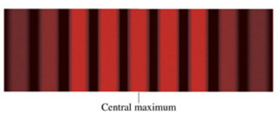


A. Closer together.
B. In the same positions.
C. Farther apart.
D. Fuzzy and out of focus.

Slide 32-37

QuickCheck 33.4

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 32-38

Example 33.1 Measuring the Wavelength of Light

EXAMPLE 33.1 | **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 32-39

Example 33.1 Measuring the Wavelength of Light

EXAMPLE 33.1 **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 33.7, 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.

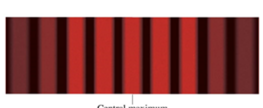
Example 33.1 Measuring the Wavelength of Light

EXAMPLE 33.1 **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 16 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.

QuickCheck 33.5

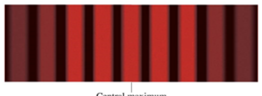
A laboratory experiment produces a double-slit interference pattern on a screen. If green light is used, with everything else the same, the bright fringes will be



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.

QuickCheck 33.5

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

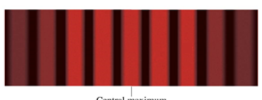


✔ **A. Closer together.**
B. In the same positions.
C. Farther apart.
D. There will be no fringes because the conditions for interference won't be satisfied.

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

QuickCheck 33.6

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.
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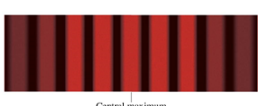
QuickCheck 33.6

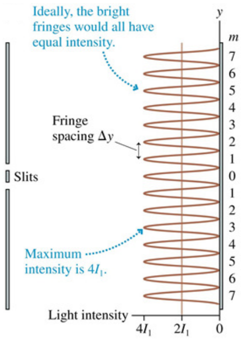
A laboratory experiment produces a double-slit interference pattern on a screen. If the slits are moved closer together, the bright fringes will be



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

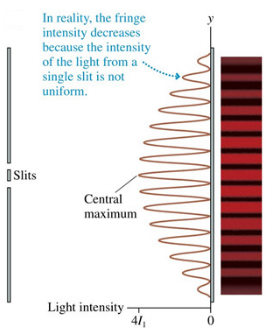


- The intensity of the double-slit interference pattern at position y is

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

 Slide 32-46

Intensity of the Double-Slit Interference Pattern



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

 Slide 32-47

QuickCheck 33.7

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

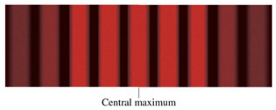
D. 8


Central maximum

 Slide 32-48

QuickCheck 33.7

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 32-49

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

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

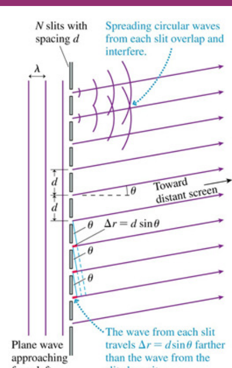
- The y-positions of these fringes will occur at

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

Slide 32-50

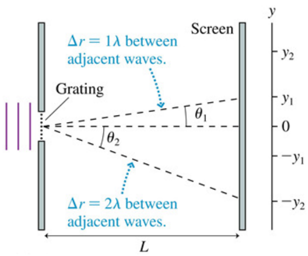
The Diffraction Grating

- 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 32-51

The Diffraction Grating



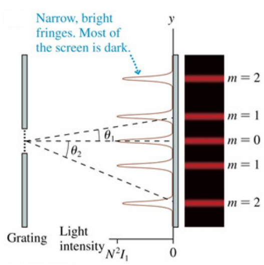
- Bright fringes will occur at angles ϕ_m, such that
  $$d \sin\phi_m = m\lambda$$
  where $m = 0, 1, 2, 3, \ldots$
- The y-positions of these fringes are:

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

Slide 32-52

The Diffraction Grating

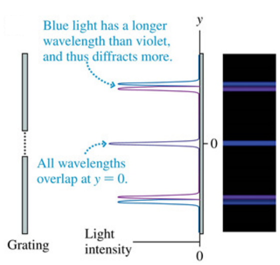
- The integer m is called the **order** of the diffraction.
- The wave amplitude at the points of constructive interference is Na.
- Because intensity depends on the square of the amplitude, the intensities of the bright fringes are
  $$I_{\max} = N^2 I_1$$



Slide 32-53

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 32-54

QuickCheck 33.8

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.

QuickCheck 33.8

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.

Example 33.2 Measuring Wavelengths Emitted by Sodium Atoms

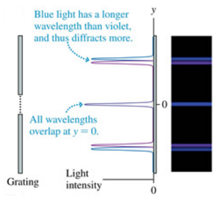
EXAMPLE 33.2 | **Measuring wavelengths emitted by sodium atoms**

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 33.2 Measuring Wavelengths Emitted by Sodium Atoms

EXAMPLE 33.2 Measuring wavelengths emitted by sodium atoms

VISUALIZE This is the situation shown in Figure 33.9b. 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 ($m = 1$).



 Slide 32-58

Example 33.2 Measuring Wavelengths Emitted by Sodium Atoms

EXAMPLE 33.2 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

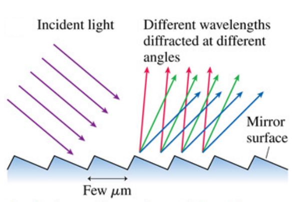
$$\lambda = d\sin\theta_1 = \begin{cases} 589.0\text{ nm} & \text{fringe at 72.88 cm} \\ 589.6\text{ nm} & \text{fringe at 73.00 cm} \end{cases}$$

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

 Slide 32-59

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.

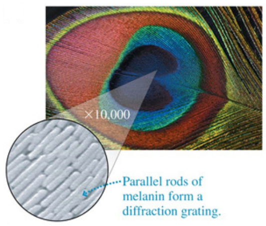


A reflection grating can be made by cutting parallel grooves in a mirror surface.

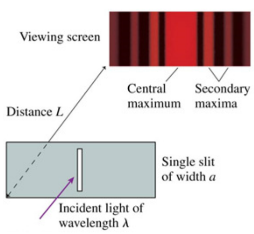
 Slide 32-60

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.

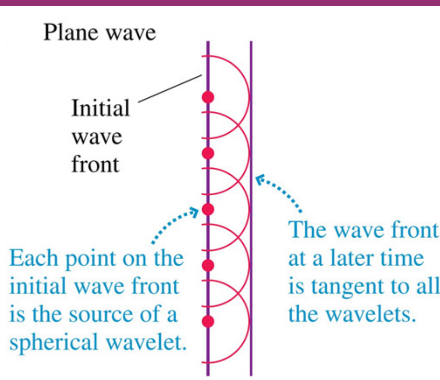


Single-Slit Diffraction

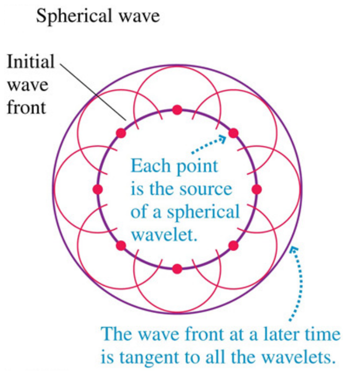


- Diffraction through a tall, narrow slit is known as single-slit diffraction.
- A viewing screen is placed distance L behind the slit of width a, and we will assume that $L >> a$.

Huygens' Principle: Plane Waves

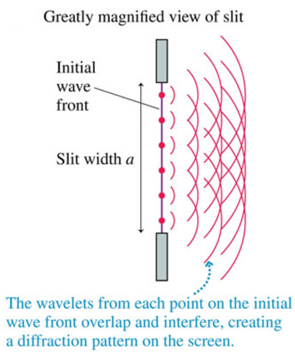


Huygens' Principle: Spherical Waves



 Slide 32-64

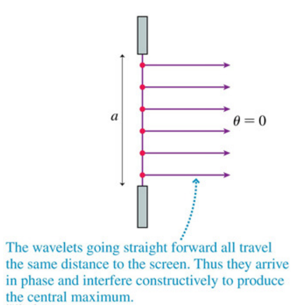
Analyzing Single-Slit Diffraction



- 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 32-65

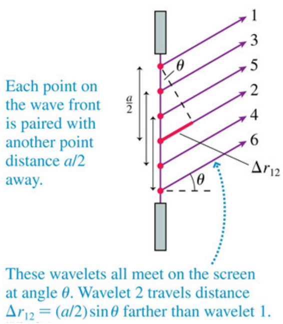
Analyzing Single-Slit Diffraction



- 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 32-66

Analyzing Single-Slit Diffraction

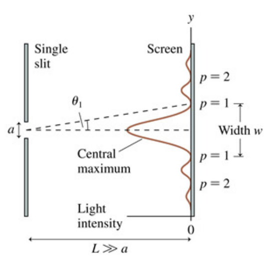


- In this figure, wavelets 1 and 2 start from points that are $a/2$ apart.
- Every point on the wave front can be paired with another point distance $a/2$ away.
- If the path-length difference is $\Delta r = \lambda/2$, the wavelets arrive at the screen out of phase and interfere destructively.

Slide 32-67

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 32-68

Example 33.3 Diffraction of a Laser Through a Slit

EXAMPLE 33.3 | 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?

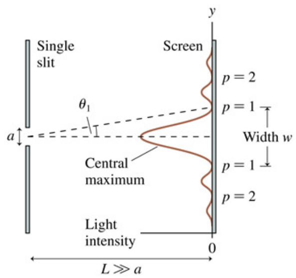
MODEL A narrow slit produces a single-slit diffraction pattern. A displacement of only 1.2 cm in a distance of 200 cm means that angle θ_1 is certainly a small angle.

Slide 32-69

Example 33.3 Diffraction of a Laser Through a Slit

EXAMPLE 33.3 Diffraction of a laser through a slit

VISUALIZE The intensity pattern will look like Figure 33.15.



 Slide 32-70

Example 33.3 Diffraction of a Laser Through a Slit

EXAMPLE 33.3 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.

 Slide 32-71

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:

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

- 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 32-72

QuickCheck 33.9

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.

QuickCheck 33.9

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 $y_p = \frac{p\lambda L}{a}$.

Example 33.4 Determining the Wavelength

EXAMPLE 33.4 | Determining the wavelength

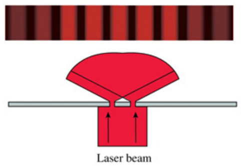
Light passes through a 0.12-mm-wide slit and forms a diffraction pattern on a screen 1.00 m behind the slit. The width of the central maximum is 0.85 cm. What is the wavelength of the light?

SOLVE From Equation 33.22, the wavelength is

$$\lambda = \frac{aw}{2L} = \frac{(1.2 \times 10^{-4}\ \text{m})(0.0085\ \text{m})}{2(1.00\ \text{m})}$$
$$= 5.1 \times 10^{-7}\ \text{m} = 510\ \text{nm}$$

QuickCheck 33.10

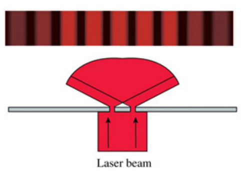
A laboratory experiment produces a double-slit interference pattern on a screen. If the left slit is blocked, the screen will look like



Slide 32-76

QuickCheck 33.10

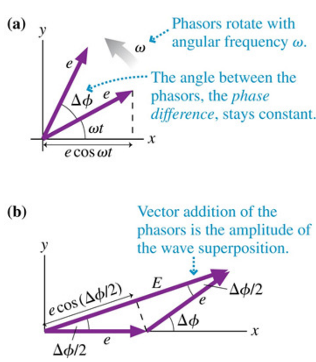
A laboratory experiment produces a double-slit interference pattern on a screen. If the left slit is blocked, the screen will look like



Slide 32-77

Advanced Topic: A Closer Look at Diffraction

- To analyze double-slit interference, we can use a *phasor diagram* to show the addition of two electric field vectors.
- The projections of the phasors onto the x-axis are what we would add in a superposition calculation.

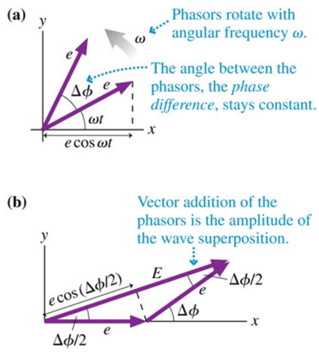


Slide 32-78

Advanced Topic: A Closer Look at Diffraction

- If we add the phasors as vectors, using the tip-to-tail method, **the magnitude E of their vector sum is the electric field amplitude of the superposition** of the two waves:

$$E = \left|2e\cos\left(\frac{\Delta\phi}{2}\right)\right|$$

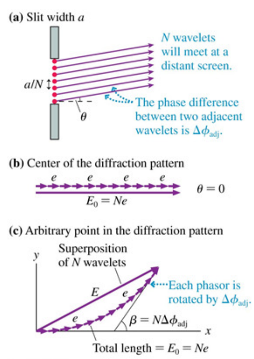


 Slide 32-79

Advanced Topic: A Closer Look at Single-Slit Diffraction

- Figure (a) shows a slit of width a with N point sources of Huygens' wavelets, each separated by distance a/N.
- Figure (b) analyzes the diffraction at the center of the diffraction pattern.
- Figure (c) is the phasor diagram for superposition at an arbitrary point on the screen.
- The angle of the last phasor is

$$\beta = N\Delta\phi_{adj} = \frac{2\pi a\sin\theta}{\lambda}$$



 Slide 32-80

Advanced Topic: A Closer Look at Single-Slit Diffraction

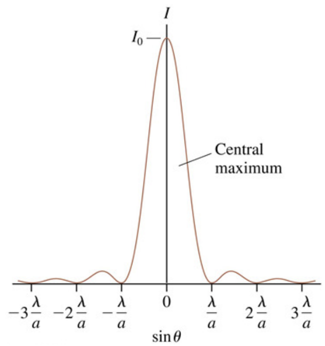
- E is the amplitude of the superposition of the N wavelets.
- To determine E, let $N\to\infty$.
- This makes our calculation exact, and it also makes our calculation easier, because now the chain of phasors, with length E_0, is simply the arc of a circle.
- From the geometry, the angle subtending this arc must be β.
- The amplitude and intensity of the superposition are

$$E = E_0\frac{\sin(\beta/2)}{\beta/2} = E_0\frac{\sin(\pi a\sin\theta/\lambda)}{\pi a\sin\theta/\lambda}$$

$$I_{slit} = I_0\left[\frac{\sin(\pi a\sin\theta/\lambda)}{\pi a\sin\theta/\lambda}\right]^2$$

 Slide 32-81

Advanced Topic: The Single-Slit Diffraction Pattern



 Slide 32-82

Advanced Topic: The Complete Double-Slit Intensity

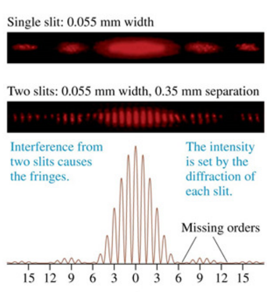
- We earlier calculated the ideal double-slit intensity for two slits separated by distance d.
- But each slit has width a, so the double-slit pattern is modulated by the single-slit diffraction intensity for a slit of width a.
- Thus a realistic double-slit intensity, for small angles, is

$$I_{\text{double}} = I_0\left[\frac{\sin(\pi ay/\lambda L)}{\pi ay/\lambda L}\right]^2 \cos^2(\pi dy/\lambda L)$$

- The cosine term produces the fringe oscillations, but now the overall intensity is determined by the diffraction of the individual slits.

 Slide 32-83

Advanced Topic: A Closer Look at Diffraction



- If an interference maximum falls exactly on a minimum (a zero) in the single-slit diffraction pattern, then we have what is called a **missing order**:

$$m_{\text{missing}} = p\frac{d}{a} \qquad p = 1, 2, 3, \ldots$$

 Slide 32-84

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

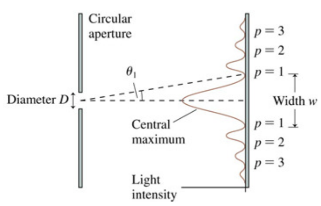
$$\theta_1 = \frac{1.22\lambda}{D}$$

- The width of the central maximum on the screen is

$$w = 2y_1 = 2L\tan\theta_1 \approx \frac{2.44\lambda L}{D} \quad \text{(circular aperture)}$$

 Slide 32-85

The Diffraction of Light by a Circular Opening



 Slide 32-86

Example 33.6 Shining a Laser Through a Circular Hole

EXAMPLE 33.6 | **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 33.31 gives us the appropriate screen distance:

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

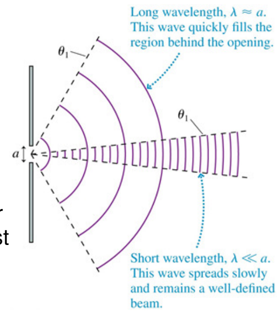
 Slide 32-87

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 $\lambda/a \ll 1$ and diffract to produce a slowly spreading "beam" of light.



QuickCheck 33.11

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,

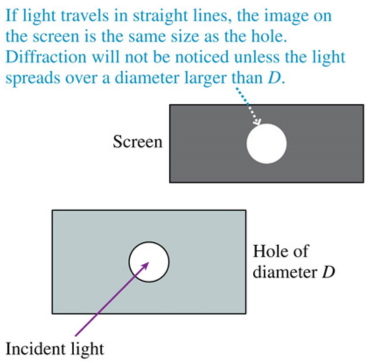
A. $\lambda < a$
B. $\lambda = a$
C. $\lambda > a$
D. Not enough info to compare λ to a

QuickCheck 33.11

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 32-91

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.

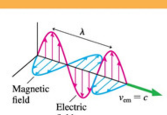
 Slide 32-92

The Wave Model of Light

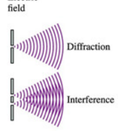
MODEL 33.1

Wave model of light

For use when diffraction is significant.



- Light is an electromagnetic wave.
  - Light travels through vacuum at speed c.
  - Wavelength λ and frequency f are related by $\lambda f = c$.
  - Most of optics depends only on the waviness of light, not on its electromagnetic properties.
- Light exhibits diffraction and interference.
  - Light spreads out after passing through an opening. The amount of spread is inversely proportional to the size of the opening.
  - Two equal-wavelength light waves interfere. Constructive and destructive interference depend on the path-length difference.
- Limitations:
  - The *ray model* is a better description in situations with no diffraction.
    Use the wave model with openings < 1 mm in size.
    Use the ray model with openings > 1 mm in size.
  - The *photon model* is a better description of extremely weak light or the light emitted in atomic transitions.



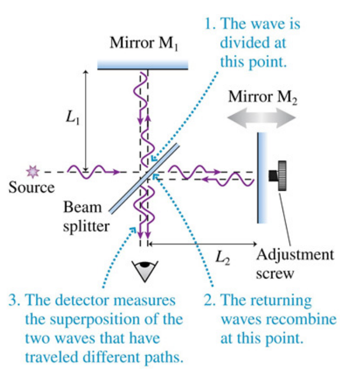
 Slide 32-93

Interferometers

- A device that uses interference to make very precise measurements is called an **interferometer**.
- Interference requires two waves of *exactly* the same wavelength.
- One way of guaranteeing that two waves have exactly equal wavelengths is to divide one wave into two parts of smaller amplitude.
- Later, at a different point in space, the two parts are recombined.
- **Interferometers are based on the division and recombination of a single wave.**

Slide 32-94

The Michelson Interferometer



Slide 32-95

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 and destructive interference will occur when

$$\text{Constructive:} \quad L_2 - L_1 = m\frac{\lambda}{2}$$
$$\text{Destructive:} \quad L_2 - L_1 = \left(m + \tfrac{1}{2}\right)\frac{\lambda}{2} \qquad m = 0, 1, 2, \ldots$$

- These equations are valid at the *center* of the beam; there is a bright or dark central spot on the detector when the first or second equation is true, respectively.

Slide 32-96

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 32-97

QuickCheck 33.12

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 32-98

QuickCheck 33.12

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 32-99

Example 33.7 Measuring the Wavelength of Light

EXAMPLE 33.7 | **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 32-100

Example 33.7 Measuring the Wavelength of Light

EXAMPLE 33.7 | **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 33.37 to find

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

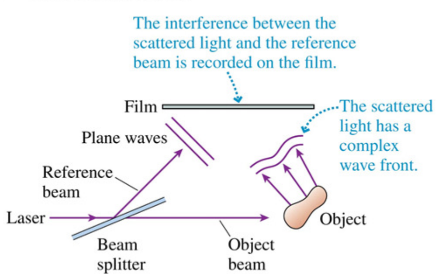
ASSESS A measurement of ΔL_2 accurate to four significant figures allowed us to determine λ to four significant figures. This happens to be the neon wavelength that is emitted as the laser beam in a helium-neon laser.

Slide 32-101

Holography

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

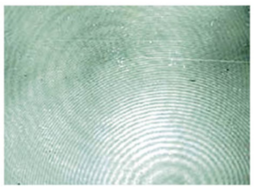
Recording a hologram



Slide 32-102

Holography

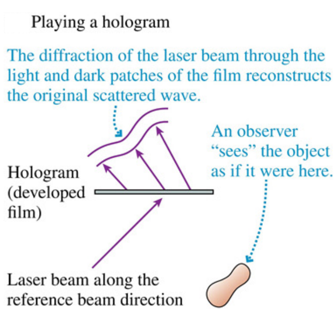
- Below is an enlarged photograph of a portion of a hologram.
- It's certainly not obvious that information is stored in this pattern, but it is.



Slide 32-103

Holography

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



Slide 32-104

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 32-105

Chapter 33 Summary Slides

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.

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.

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 $D_c \approx \sqrt{2\lambda L}$.

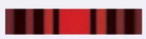
In practice, $D_c \approx 1$ mm for visible light. Thus

- 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 32-109

Applications

Single slit of width a.
A bright **central maximum** of width



$$w = \frac{2\lambda L}{a}$$

is flanked by weaker **secondary maxima.**
Dark fringes are located at angles such that

$$a \sin\theta_p = p\lambda \qquad p = 1, 2, 3, \ldots$$

If $\lambda/a \ll 1$, then from the small-angle approximation

$$\theta_p = \frac{p\lambda}{a} \qquad y_p = \frac{p\lambda L}{a}$$

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Applications

Circular aperture of diameter D.
A bright central maximum of diameter

$$w = \frac{2.44\lambda L}{D}$$

is surrounded by circular secondary maxima.
The first dark fringe is located at

$$\theta_1 = \frac{1.22\lambda}{D} \qquad y_1 = \frac{1.22\lambda L}{D}$$

For an aperture of any shape, a smaller opening causes a more rapid spreading of the wave behind the opening.

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Applications

Interference due to wave-front division

Waves overlap as they spread out behind slits. Constructive interference occurs along antinodal lines. Bright fringes are seen where the antinodal lines intersect the viewing screen.

Double slit with separation d.
Equally spaced bright fringes are located at

$$\theta_m = \frac{m\lambda}{d} \qquad y_m = \frac{m\lambda L}{d} \qquad m = 0, 1, 2, \ldots$$

The **fringe spacing** is $\Delta y = \frac{\lambda L}{d}$

Diffraction grating with slit spacing d.
Very bright and narrow fringes are located at angles and positions

$$d \sin\theta_m = m\lambda \qquad y_m = L\tan\theta_m$$

Applications

Interference due to amplitude division

An interferometer divides a wave, lets the two waves travel different paths, then recombines them. Interference is constructive if one wave travels an integer number of wavelengths more or less than the other wave. The difference can be due to an actual path-length difference or to a different index of refraction.

Michelson interferometer

The number of bright-dark-bright fringe shifts as mirror M_2 moves distance ΔL_2 is

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