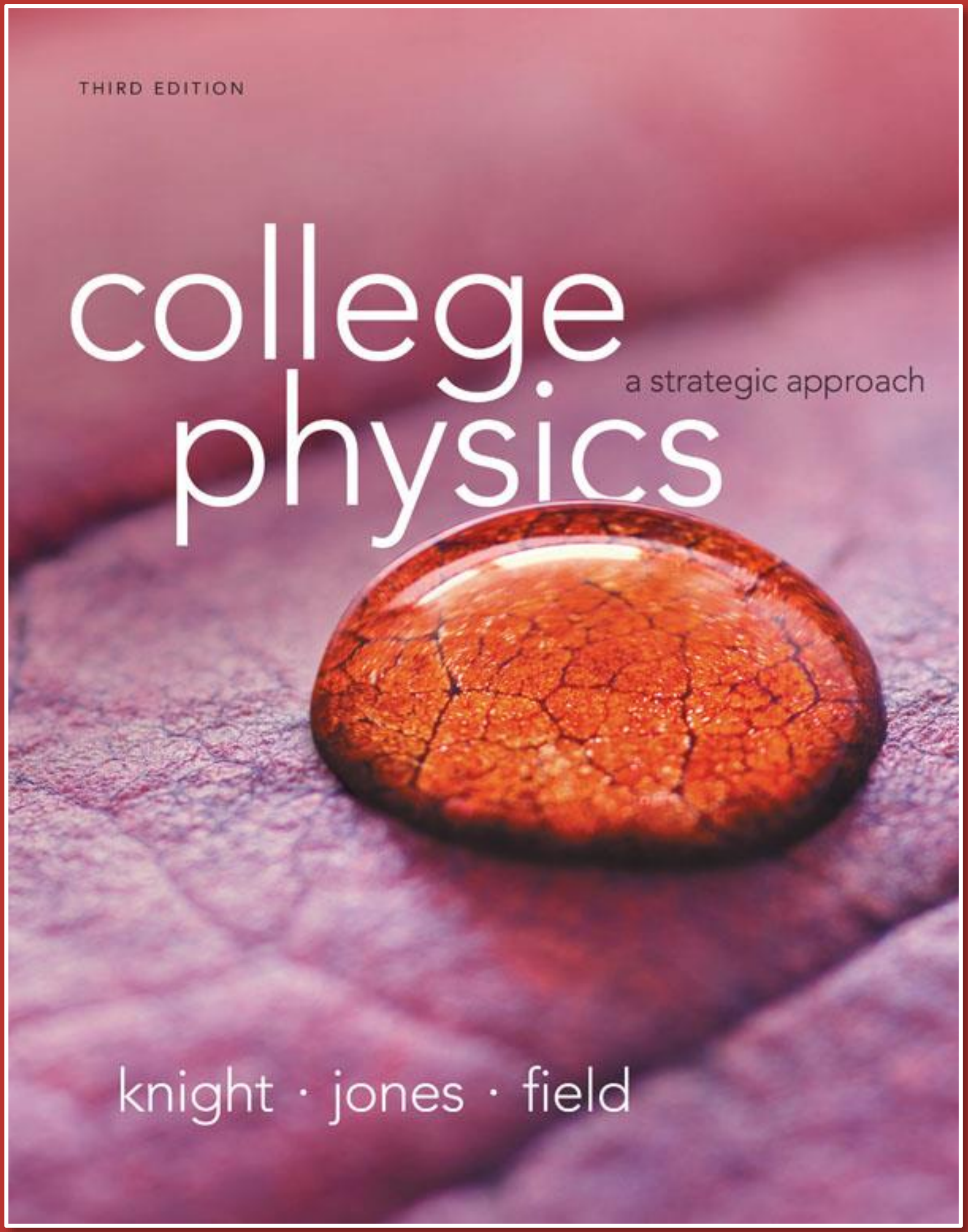


Lecture Presentation

Chapter 17

Wave Optics

Suggested Videos for Chapter 17

- **Prelecture Videos**
  - *Diffraction and Interference*
  - *Thin-Film Interference*
- **Class Videos**
  - *Reflection Grating*
- **Video Tutor Solutions**
  - *Wave Optics*

Suggested Simulations for Chapter 17

- **ActivPhysics**
  - *16.1–16.7*
- **PhETs**
  - *Wave Interference*

Chapter 17 Wave Optics

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

Chapter 17 Preview
Looking Ahead: The Wave Model of Light

- The varying colors reflected from this DVD can be understood using the **wave model** of light, which is the focus of this chapter.

- You'll learn that the wave model applies when light passes through small apertures or when waves from several small sources combine.

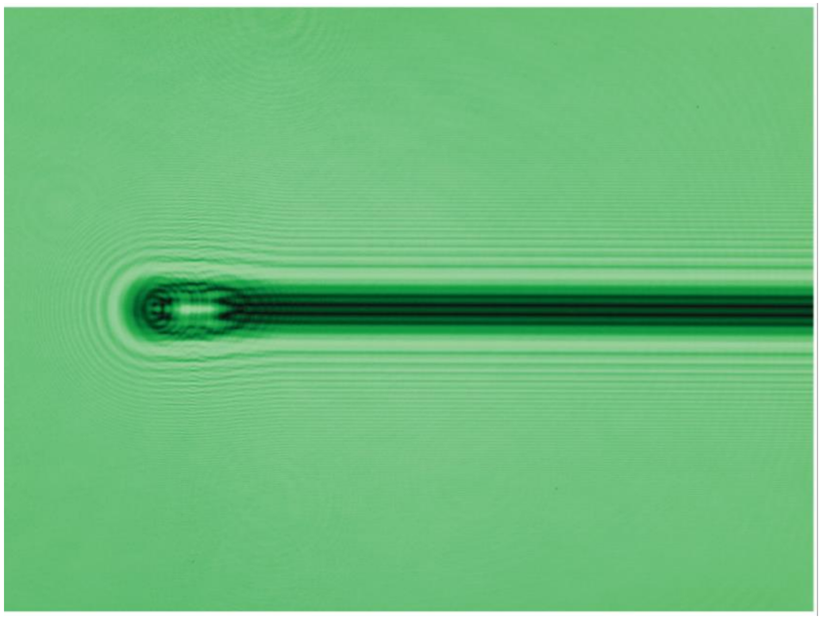
Chapter 17 Preview
Looking Ahead: Interference

- The beetle's colorful look is the result of interference between light waves reflecting off microscopic layers of its shell.

- You'll learn how light waves from two or more sources can interfere constructively or destructively.

Chapter 17 Preview
Looking Ahead: Diffraction

- The light waves passing this sewing needle are slightly bent, or *diffracted*, causing the bands seen in the image.



- You'll learn how **diffraction** occurs for light passing through a narrow slit or a small, circular aperture.

Chapter 17 Preview
Looking Ahead

The Wave Model of Light

The varying colors reflected from this DVD can be understood using the **wave model** of light, which is the focus of this chapter.

You'll learn that the wave model applies when light passes through small apertures or when waves from several small sources combine.

Interference

This beetle's colorful look is the result of **interference** between light waves reflecting off microscopic layers of its shell.

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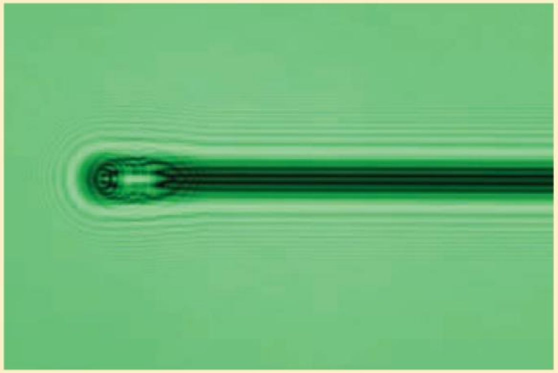
Diffraction

The light waves passing this sewing needle are slightly bent, or *diffracted*, causing the bands seen in the image.

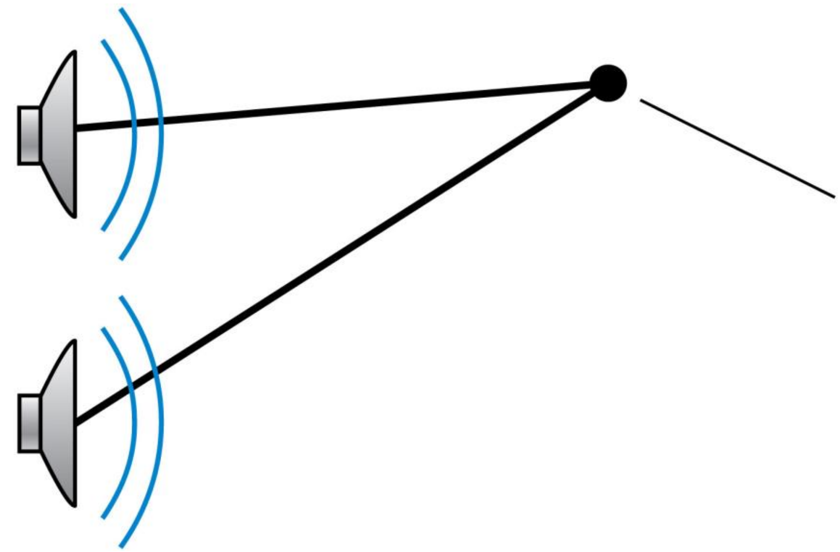


You'll learn how **diffraction** occurs for light passing through a narrow slit or a small, circular aperture.

Text: p. 536

Chapter 17 Preview
Looking Back: Interference of Two Waves

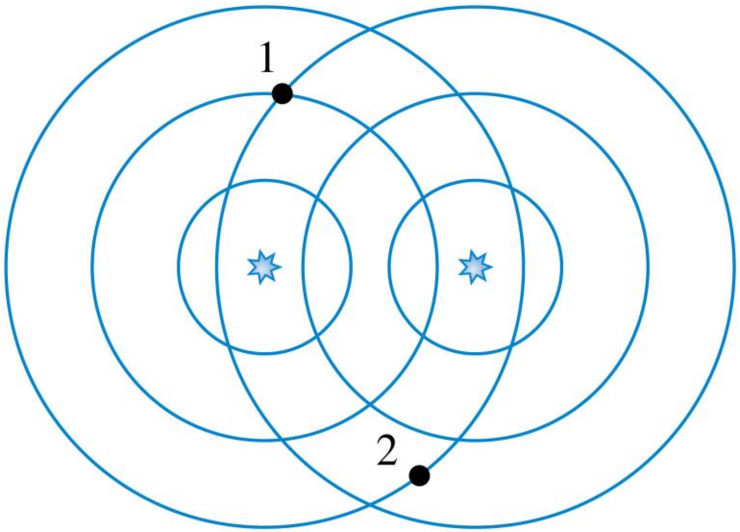
- In Section 16.6, you studied the interference of sound waves. We'll use these same ideas when we study the interference of light waves in this chapter.



- You learned that waves interfere constructively at a point if their path-length difference is an integer number of wavelengths.

Chapter 17 Preview
Stop to Think

Sound waves spread out from two speakers; the circles represent crests of the spreading waves. The interference is



A. Constructive at both points 1 and 2.
B. Destructive at both points 1 and 2.
C. Constructive at 1, destructive at 2.
D. Destructive at 1, constructive at 2.

Reading Question 17.1

Any kind of wave spreads out after passing through a small enough gap in a barrier. This phenomenon is known as

A. Antireflection.
B. Double-slit interference.
C. Refraction.
D. Diffraction.

Reading Question 17.1

Any kind of wave spreads out after passing through a small enough gap in a barrier. This phenomenon is known as

A. Antireflection.
B. Double-slit interference.
C. Refraction.
✔ D. Diffraction.

Reading Question 17.2

The wave model of light is needed to explain many of the phenomena discussed in this chapter. Which of the following can be understood *without* appealing to the wave model?

A. Single-slit diffraction
B. Thin-film interference
C. Sharp-edged shadows
D. Double-slit interference

Reading Question 17.2

The wave model of light is needed to explain many of the phenomena discussed in this chapter. Which of the following can be understood *without* appealing to the wave model?

A. Single-slit diffraction
B. Thin-film interference
✔ C. Sharp-edged shadows
D. Double-slit interference

Reading Question 17.3

As the number of slits of a diffraction grating increases, the bright fringes observed on the viewing screen

A. Get wider.
B. Get narrower.
C. Increase in number.
D. Decrease in number.

Reading Question 17.3

As the number of slits of a diffraction grating increases, the bright fringes observed on the viewing screen

A. Get wider.
✔ B. Get narrower.
C. Increase in number.
D. Decrease in number.

Reading Question 17.4

The colors of a soap bubble or oil slick are due to

A. Diffraction.
B. Two-slit interference.
C. Thin-film interference.
D. Huygens' principle.

Reading Question 17.4

The colors of a soap bubble or oil slick are due to

A. Diffraction.

B. Two-slit interference.

✔ C. Thin-film interference.

D. Huygens' principle.

Reading Question 17.5

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.

Reading Question 17.5

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.

Section 17.1 What is Light?

What Is Light?

- Under some circumstances, light acts like particles traveling in straight lines, while in other circumstances light shows the same kinds of wave-like behavior as sound waves or water waves.
- Change the circumstances yet again, and light exhibits behavior that is neither wave-like nor particle-like but has characteristics of both.

What Is Light?

- We develop three **models of light**. Each model successfully explains the behavior of light within a certain domain.

What Is Light?

The Wave Model

The wave model of light is the most widely applicable model, responsible for the widely known “fact” that light is a wave. It is certainly true that, under many circumstances, light exhibits the same behavior as sound or water waves. Lasers and electro-optical devices, critical technologies of the 21st century, are best understood in terms of the wave model of light. Some aspects of the wave model of light were introduced in Chapters 15 and 16, and the wave model is the primary focus of this chapter. The study of light as a wave is called **wave optics.**

What Is Light?

The Ray Model

An equally well-known "fact" is that light travels in a straight line. These straight-line paths are called *light rays*. The properties of prisms, mirrors, lenses, and optical instruments such as telescopes and microscopes are best understood in terms of light rays. Unfortunately, it's difficult to reconcile the statement "light travels in a straight line" with the statement "light is a wave." For the most part, waves and rays are mutually exclusive models of light. An important task will be to learn when each model is appropriate. The ray model of light, the basis of **ray optics,** is the subject of the next chapter.

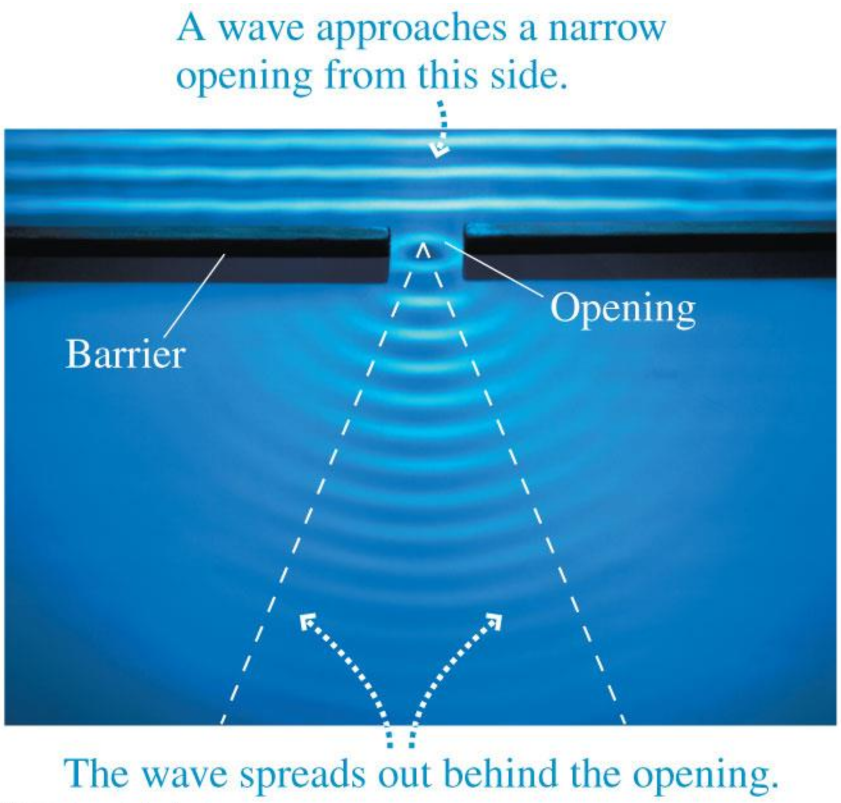
What Is Light?

The Photon Model

Modern technology is increasingly reliant on quantum physics. In the quantum world, light consists of *photons* that have both wave-like and particle-like properties. Photons are the *quanta* of light. Much of the quantum theory of light is beyond the scope of this textbook, but we will take a peek at the important ideas in Chapters 25 and 28 of this text.

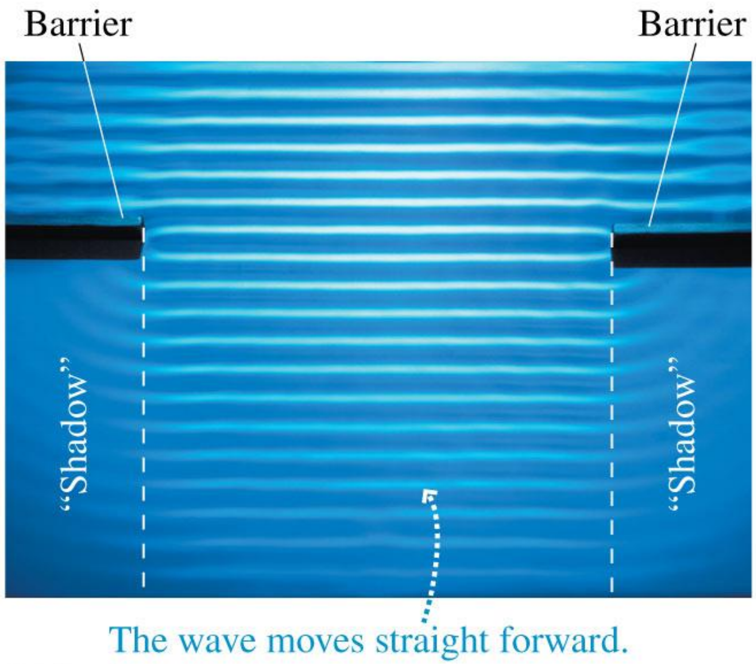
The Propagation of Light Waves

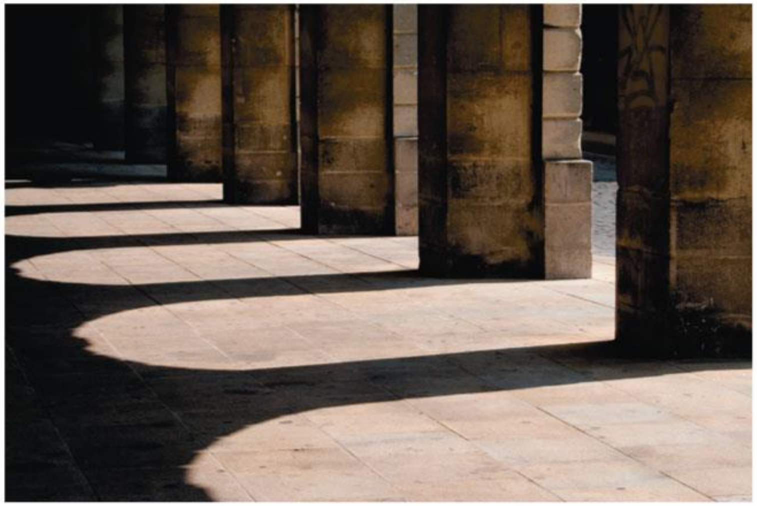
- A water wave passes through a window-like opening in a barrier.
- The wave *spreads out* to fill the space behind the opening. This phenomenon is called **diffraction**.
- Diffraction is a clear sign that a wave is passing through the opening.



The Propagation of Light Waves

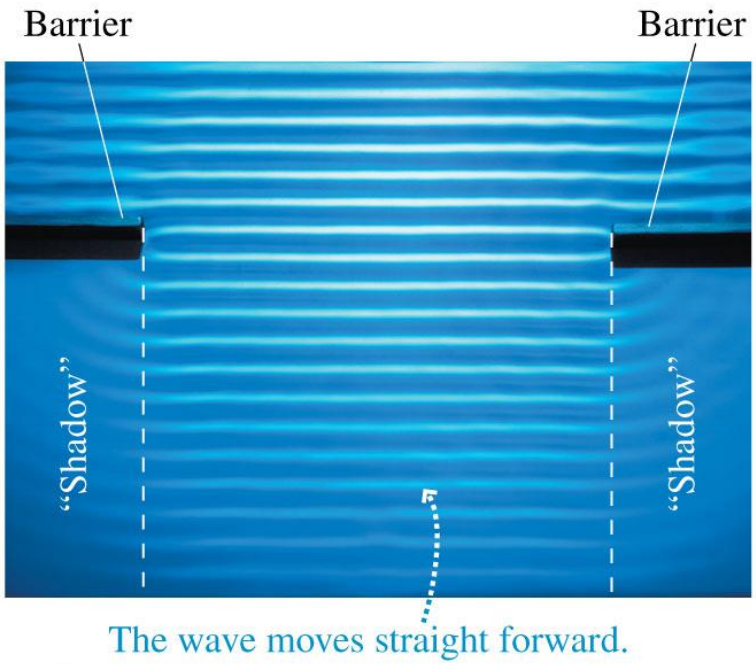
- When the opening is many times larger than the wavelength of the wave, the wave continues to move straight forward.
- There is a defined region, the “shadow,” where there is no wave.
- This is similar to the straight-line appearance of light with sharp shadows as light passes through large windows.

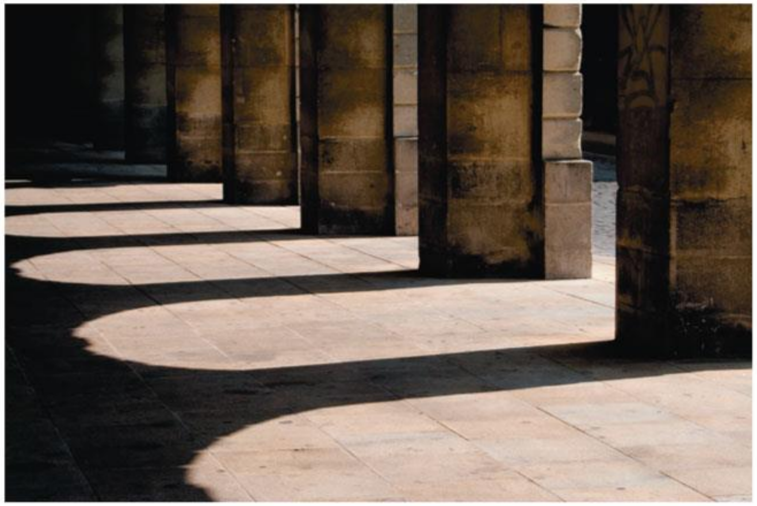




The Propagation of Light Waves

- Whether a wave spreads out (diffracts) or travels straight ahead with sharp shadows on either side depends on the size of the objects that the wave interacts with.
- Diffraction becomes noticeable when the opening is comparable in size to the wavelength of the wave.





Light Is an Electromagnetic Wave

- Light consists of very rapidly oscillating electric and magnetic fields: It is an *electromagnetic wave*.
- All electromagnetic waves travel in a vacuum at the *speed of light*:

$$v_{\text{light}} = c = 3.00 \times 10^8 \text{ m/s}$$

- Visible light wavelengths range from 400 nm–700 nm. This is the *visible spectrum*.
- Because the wavelengths are very short, the frequencies of visible light are very high. For a 600 nm wavelength

$$f = \frac{v}{\lambda} = \frac{3.00 \times 10^8 \text{ m/s}}{600 \times 10^{-9} \text{ m}} = 5.00 \times 10^{14} \text{ Hz}$$

The Index of Refraction

- Light waves slow down as they pass through transparent materials such as water, glass, or air. This is due to the interactions between the electromagnetic field of the wave and the electrons in the material.
- The speed of light in a material is characterized by the material's **index of refraction** *n*, defined by

$$n = \frac{\text{speed of light in a vacuum}}{\text{speed of light in the material}} = \frac{c}{v}$$

- *n* is always greater than 1 because *v* is always less than *c*. A vacuum has $n = 1$.

The Index of Refraction

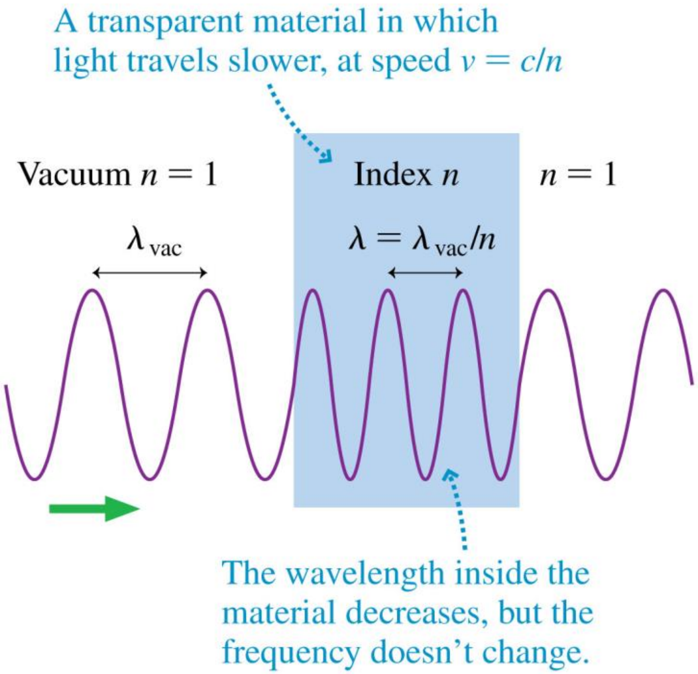
TABLE 17.1 Typical indices of refraction

Material	Index of refraction
Vacuum	1 exactly
Air	1.0003
Water	1.33
Glass	1.50
Diamond	2.42

The Index of Refraction

- **The frequency of a wave does not change as the wave moves from one medium to another.**
- Therefore the wavelength must change. The wavelength of light in a material is

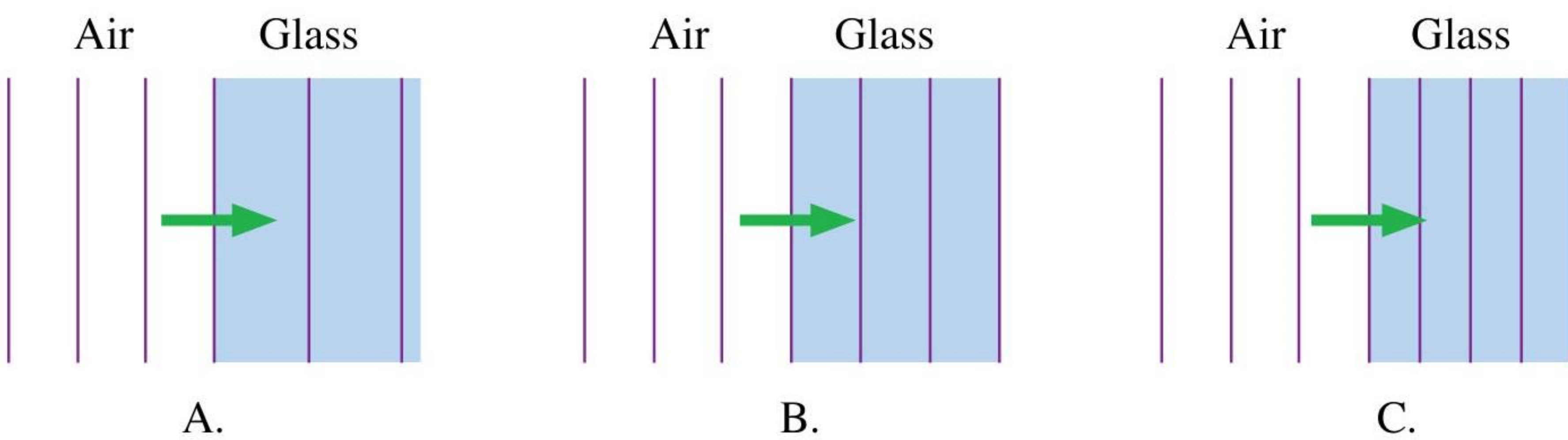
$$\lambda_{\text{mat}} = \frac{v}{f_{\text{mat}}} = \frac{c}{nf_{\text{mat}}} = \frac{c}{nf_{\text{vac}}} = \frac{\lambda_{\text{vac}}}{n}$$



- **The wavelength in the transparent material is shorter than the wavelength in a vacuum.**

QuickCheck 17.1

A light wave travels, as a plane wave, from air (n = 1.0) into glass (n = 1.5). Which diagram shows the correct wave fronts?



QuickCheck 17.1

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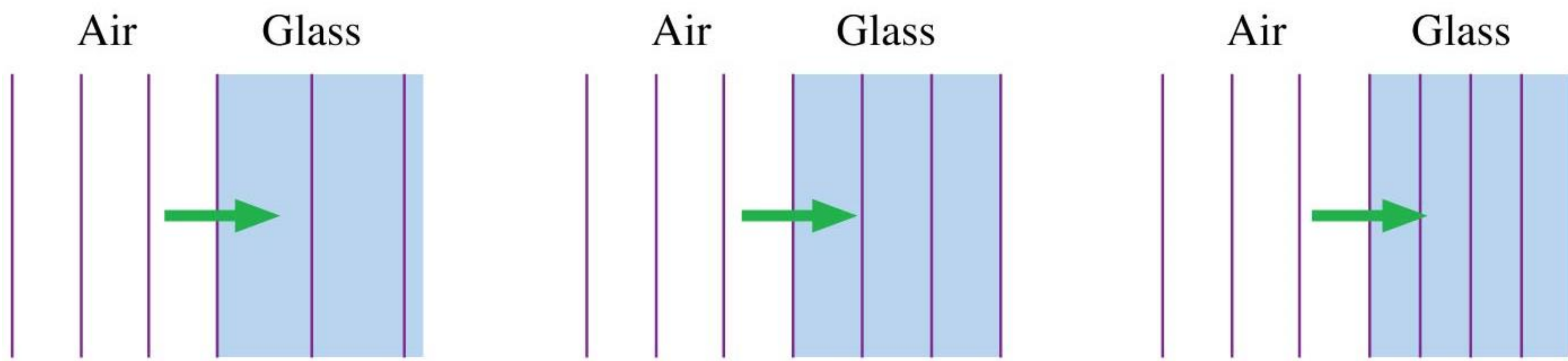


A. B. ✔ C.

Example 17.1 Analyzing light traveling through a glass

Orange light with a wavelength of 600 nm is incident on a 1.00-mm-thick glass microscope slide.

a. What is the light speed in the glass?

b. How many wavelengths of the light are inside the slide?

Example 17.1 Analyzing light traveling through a glass (cont.)

SOLVE

a. From Table 17.1 we see that the index of refraction of glass is $n_{\text{glass}} = 1.50$. Thus the speed of light in glass is

$$v_{\text{glass}} = \frac{c}{n_{\text{glass}}} = \frac{3.00 \times 10^8 \text{ m/s}}{1.50} = 2.00 \times 10^8 \text{ m/s}$$

Example 17.1 Analyzing light traveling through a glass (cont.)

b. Because $n_{\text{air}} = 1.00$, the wavelength of the light is the same in air and vacuum: $\lambda_{\text{vac}} = \lambda_{\text{air}} = 600$ nm. Thus the wavelength inside the glass is

$$\lambda_{\text{glass}} = \frac{\lambda_{\text{vac}}}{n_{\text{glass}}} = \frac{600 \text{ nm}}{1.50} = 400 \text{ nm} = 4.00 \times 10^{-7} \text{ m}$$

Example 17.1 Analyzing light traveling through a glass (cont.)

N wavelengths span a distance $d = N\lambda$, so the number of wavelengths in $d = 1.00$ mm is

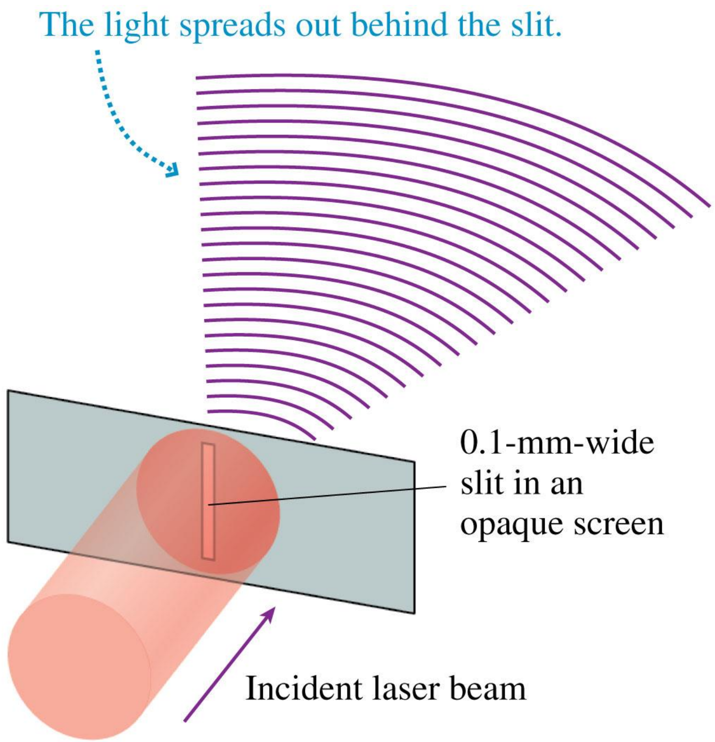
$$N = \frac{d}{\lambda} = \frac{1.00 \times 10^{-3}\ \text{m}}{4.00 \times 10^{-7}\ \text{m}} = 2500$$

ASSESS The fact that 2500 wavelengths fit within 1 mm shows how small the wavelengths of light are.

Section 17.2 The Interference of Light

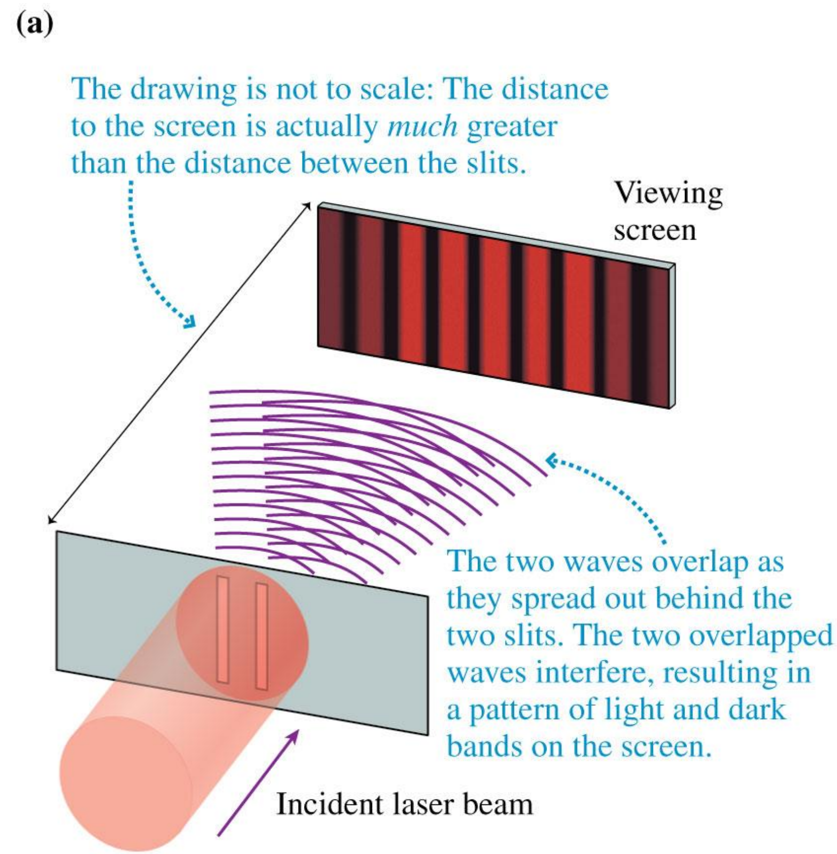
The Interference of Light

- Because light acts as a wave, light waves can overlap and *interfere* constructively and destructively.
- We use very small slits to create waves that can interfere with each other. When the light wave passes through the slit, it diffracts, a sure sign of waviness.



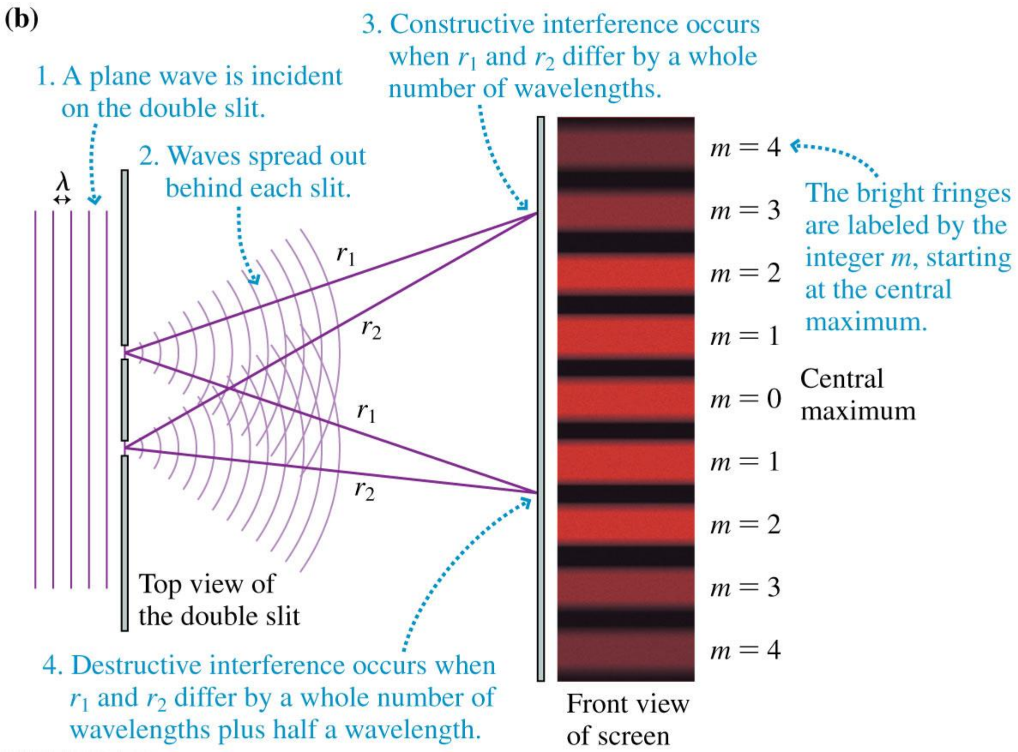
Young's Double-Slit Experiment

- In order to observe interference, we need *two* light sources whose waves can overlap and interfere.
- In an experiment first performed by Thomas Young in 1801, light (in our case, a laser) is shown through a pair of slits, a **double slit**. Light passing through the slits impinges on a viewing screen.



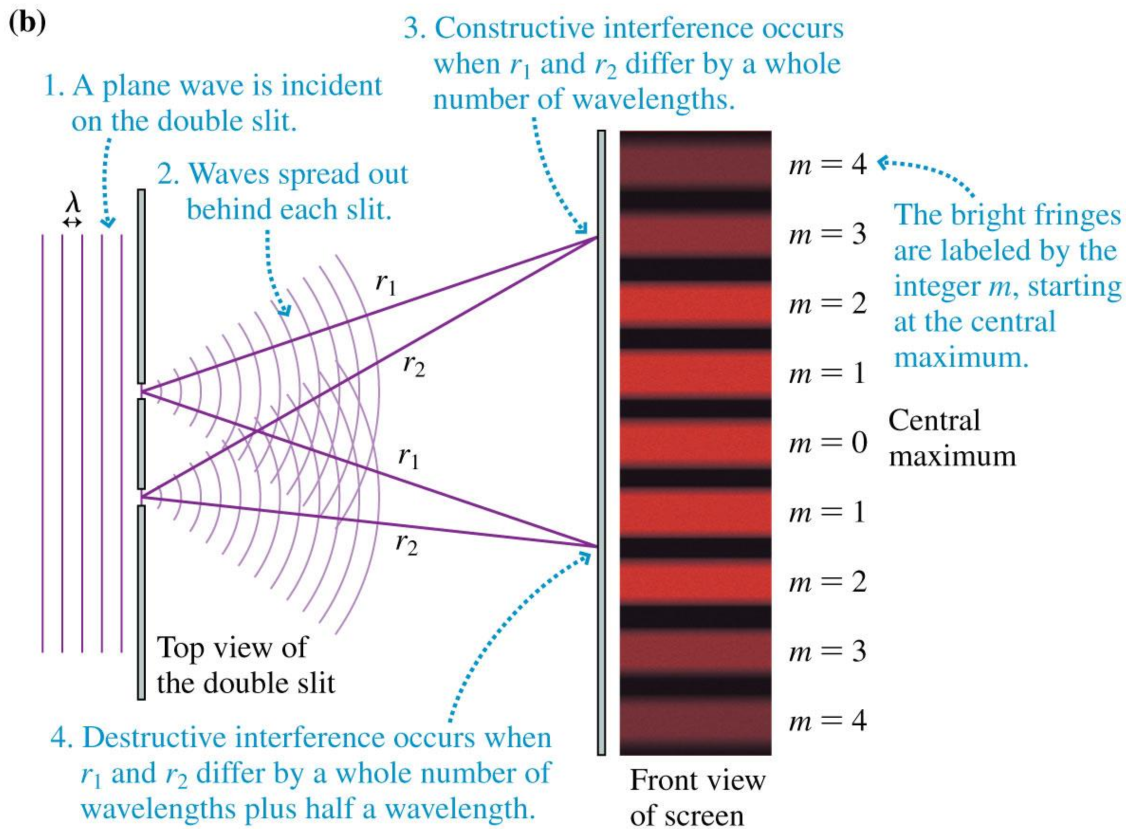
Young's Double-Slit Experiment

- **Light spreads out behind each slit.**
- As with the sound waves, constructive interference occurs at a point where distances r_1 and r_2 from the slits differ by a whole number of wavelengths. Constructive interference is seen as a higher intensity of light on the viewing screen.



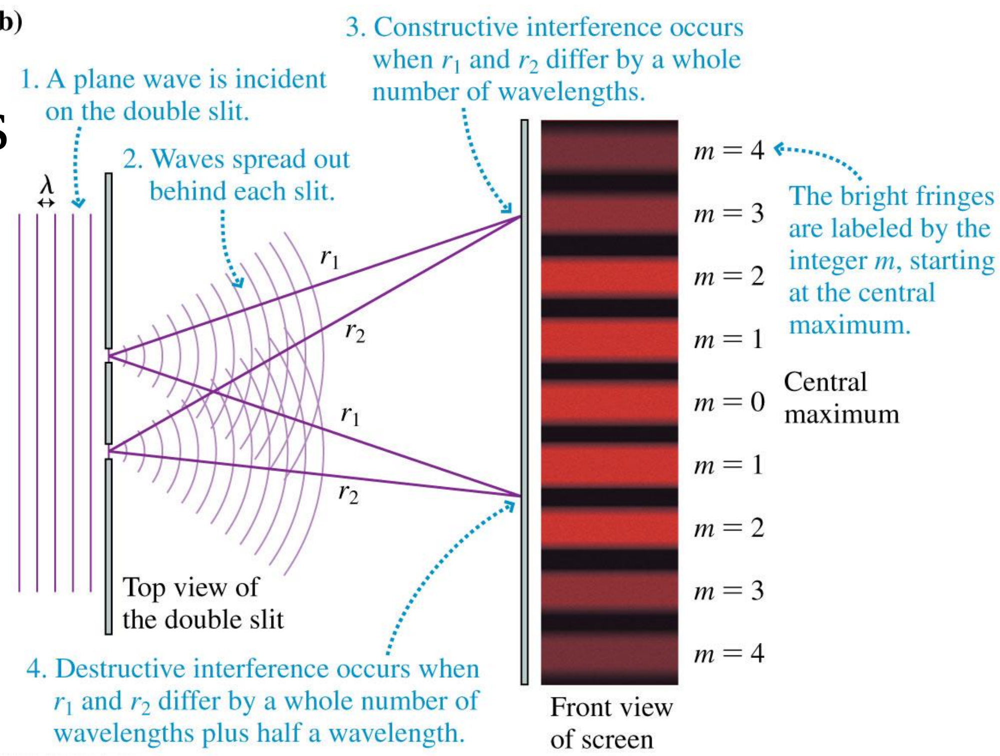
Young's Double-Slit Experiment

- Destructive interference will occur when the light waves occur at positions on the screen for which r_1 and r_2 differ by a whole number of wavelengths plus half a wavelength.



Young's Double-Slit Experiment

- Along the viewing screen, the difference Δr alternates between being a whole number of wavelengths and a whole number of wavelengths plus half a wavelength, leading to a series of alternating bright and dark bands of light called **interference fringes.**



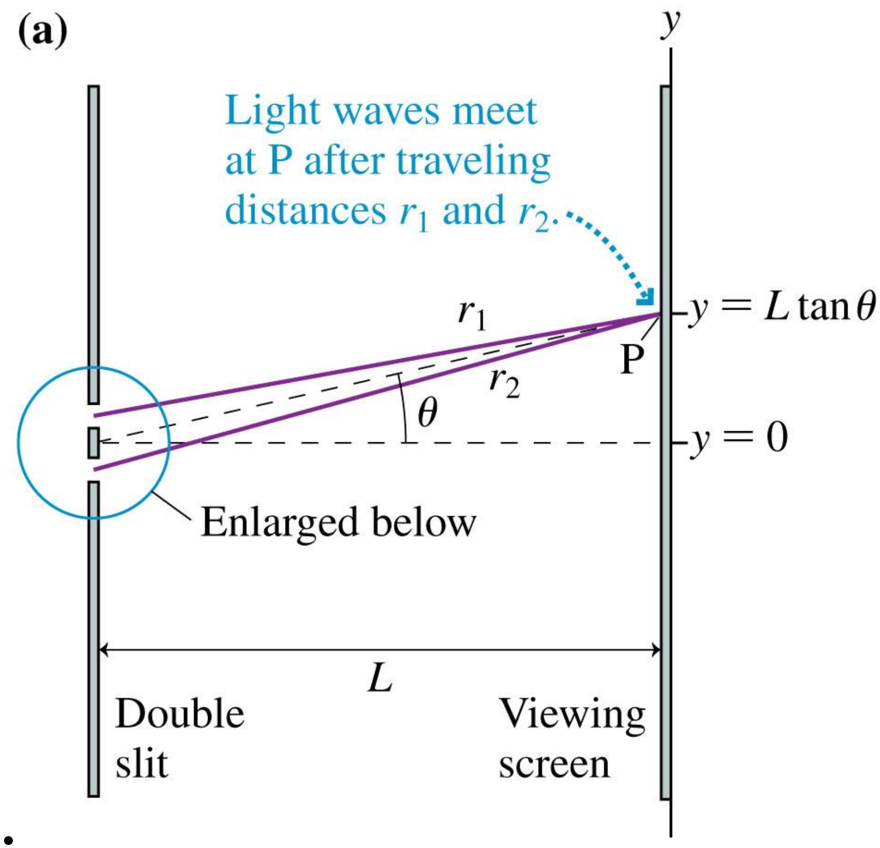
- The **central maximum** is the brightest fringe at the midpoint of the screen.

Analyzing Double-Slit Interference

- The double slit experiment consists of a double slit spaced d apart and a distance L to the viewing screen. **We assume L is *very* much larger than d.**
- Constructive interference occurs when

$$\Delta r = m\lambda \quad m = 0, 1, 2, 3, \ldots$$

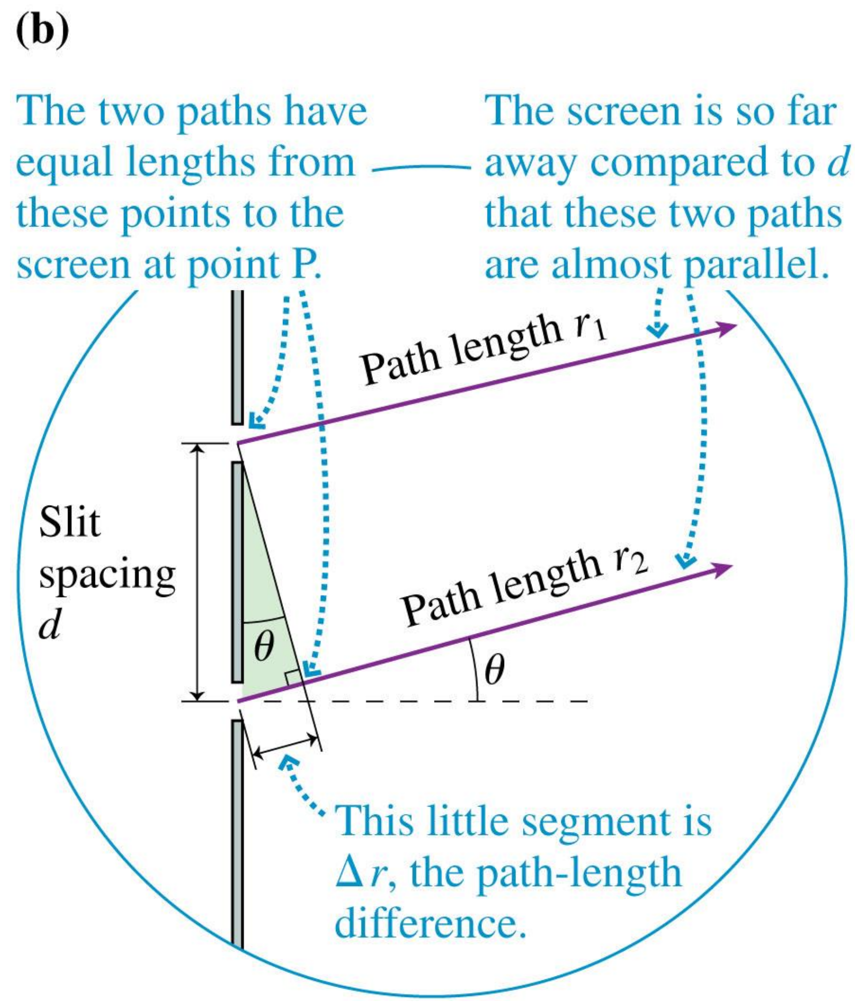
- It produces a bright fringe at that point.



Analyzing Double-Slit Interference

- We must find the positions on the screen where $\Delta r = m\lambda$.
- Point P on the screen is a distance y from the center of the viewing screen, or an angle θ from the line connecting the center of the slit to the center of the screen. They are related:

$$y = L \tan \theta$$



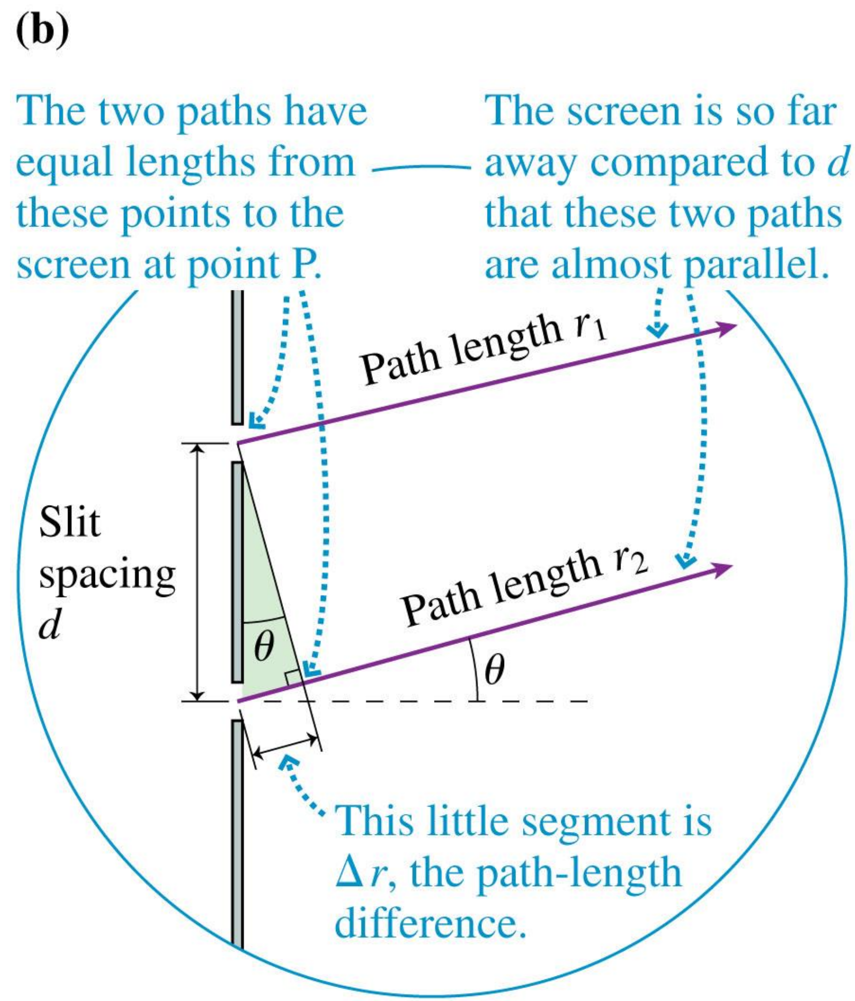
Analyzing Double-Slit Interference

- Because point P is very far compared to the spacing between slits, the two paths to point P are virtually parallel.
- Therefore the path-length difference is the short side of the triangle:

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

- So the bright fringes occur:

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



Analyzing Double-Slit Interference

- The center of the viewing screen at $y = 0$ is equally distant from both slits, so $\Delta r = 0$ with $m = 0$, which is where the brightest fringe (the central maximum) occurs.
- As you move away from the center, the ***m*th bright fringe occurs where one wave has traveled *m* wavelengths farther than the other and thus $\Delta r = m\lambda$.**

Analyzing Double-Slit Interference

- We can use the *small angle approximation* to rewrite the angular position (in *radians*) of the fringes as

$$\theta_m = m\frac{\lambda}{d} \qquad m = 0, 1, 2, 3, \ldots$$

Angles (in radians) of bright fringes for double-slit interference with slit spacing *d*

- It is more convenient to measure the *position* of the *m*th bright fringe, as measured from the center of the viewing screen:

$$y_m = \frac{m\lambda L}{d} \qquad m = 0, 1, 2, 3, \ldots$$

Positions of bright fringes for double-slit interference at screen distance *L*

Analyzing Double-Slit Interference

- The equations show that **the interference pattern is a series of equally spaced bright lines** on the screen. The **fringe spacing** between fringe *m* and fringe *m* + 1 is

$$\Delta y = y_{m+1} - y_m = \frac{(m+1)\lambda L}{d} - \frac{m\lambda L}{d}$$

$$\Delta y = \frac{\lambda L}{d}$$

Spacing between any two adjacent bright fringes

Analyzing Double-Slit Interference

- The dark fringes are bands of destructive interference where the path-length difference of the waves is a whole number of wavelengths plus half a wavelength:

$$\Delta r = \left(m + \frac{1}{2}\right)\lambda \qquad m = 0, 1, 2, 3, \ldots$$

- We use the relationship of the path-length difference with the angular separation of the fringes found earlier:

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

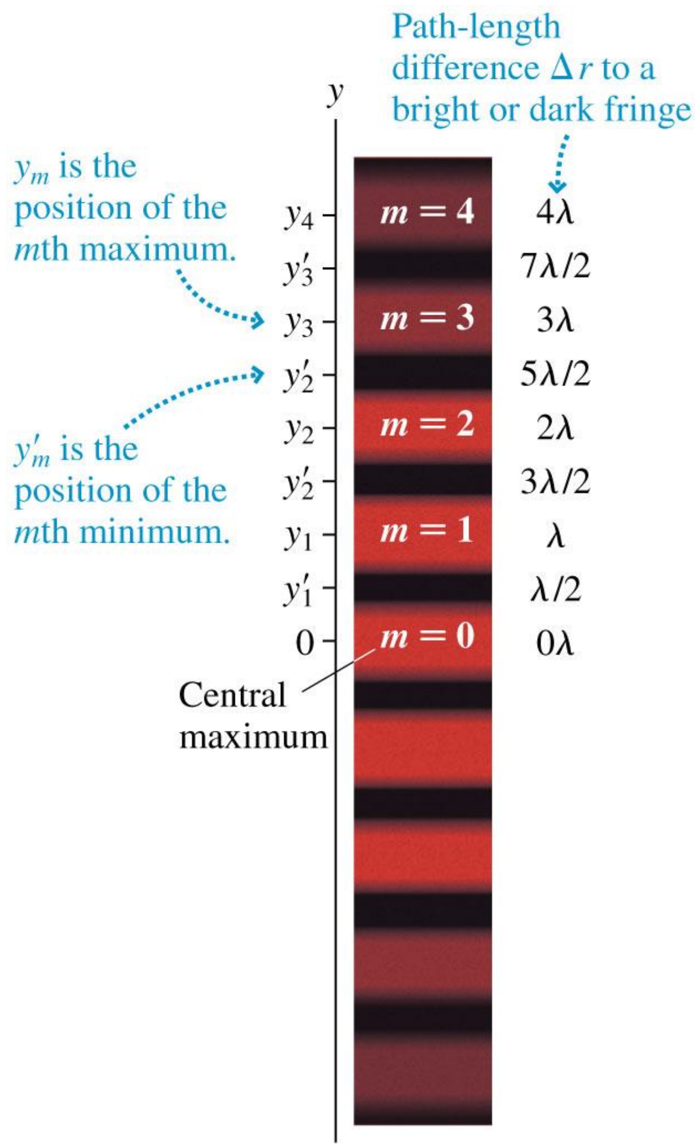
Analyzing Double-Slit Interference

- Combining the previous equations, we find that the dark fringes are located at the positions

$$y'_m = \left(m + \frac{1}{2}\right)\frac{\lambda L}{d} \qquad m = 0, 1, 2, 3, \ldots$$

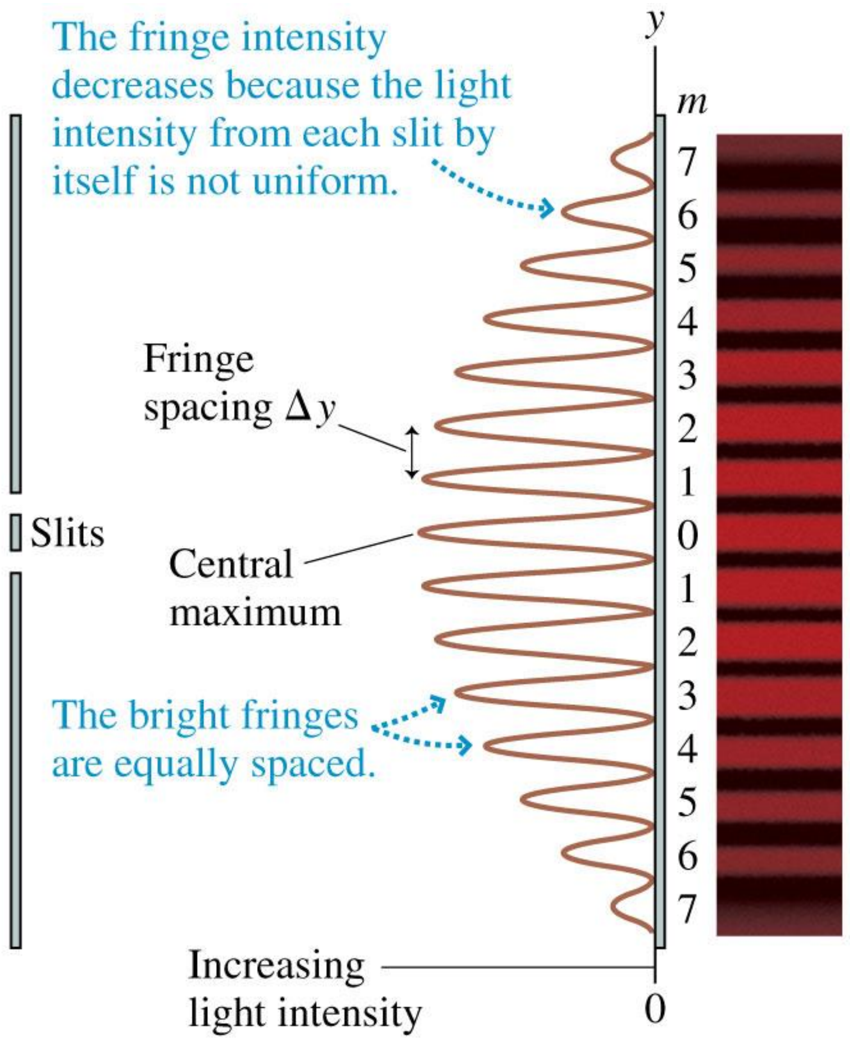
Positions of dark fringes for double-slit interference

- **The dark fringes are located exactly halfway between the bright fringes.**



Analyzing Double-Slit Interference

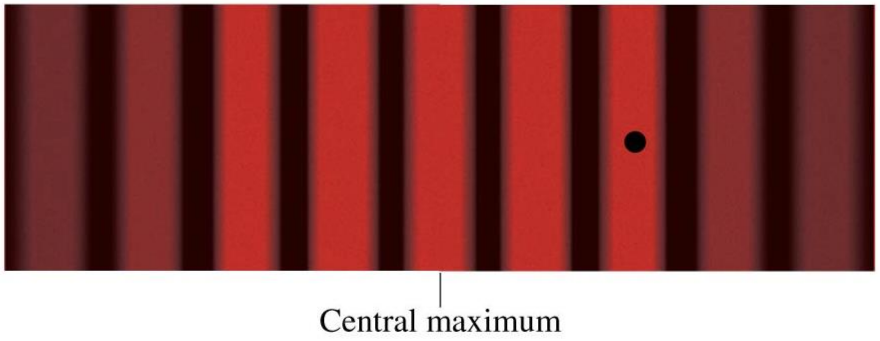
- The intensity of the light oscillates between dark fringes, where the intensity is zero and the bright fringes are of maximum intensity.



QuickCheck 17.2

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



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✔ C. 2.0 λ
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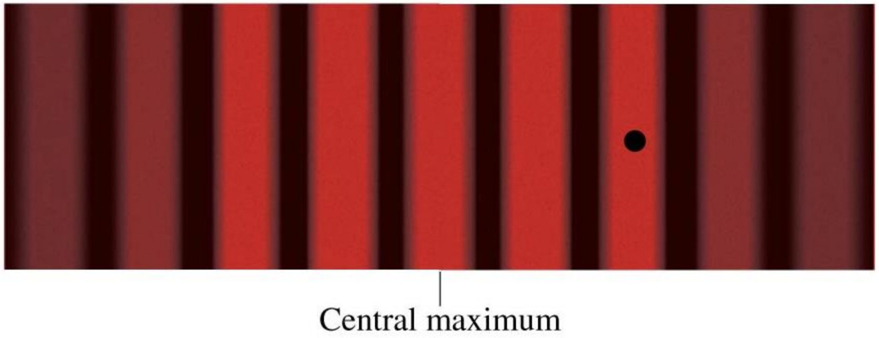
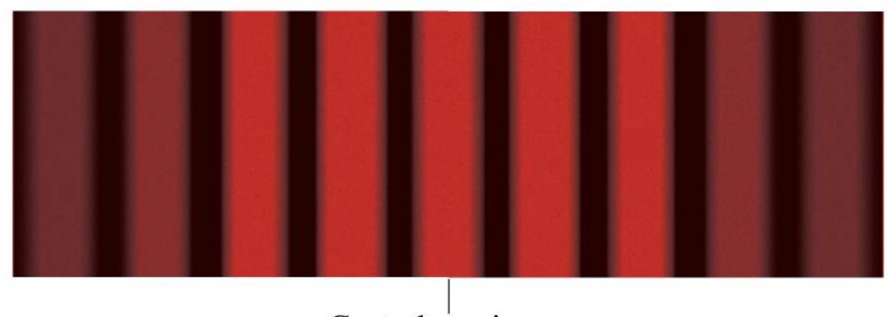


QuickCheck 17.3

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.



QuickCheck 17.3

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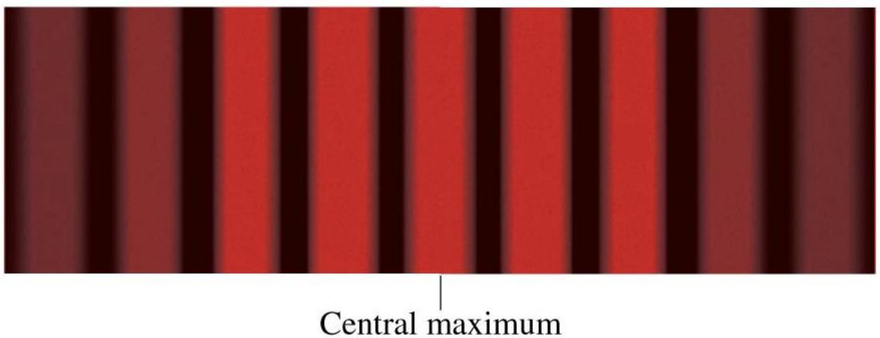
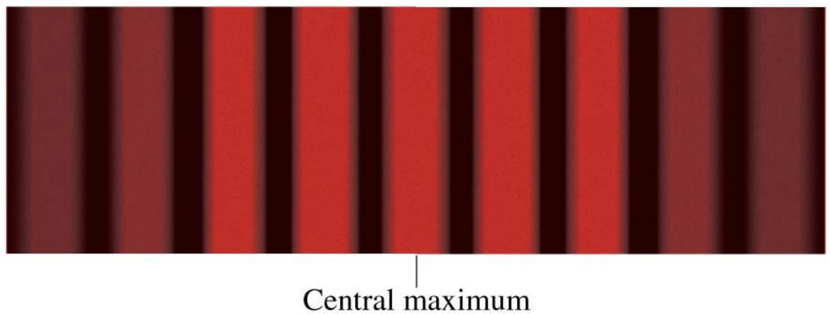


QuickCheck 17.4

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 17.4

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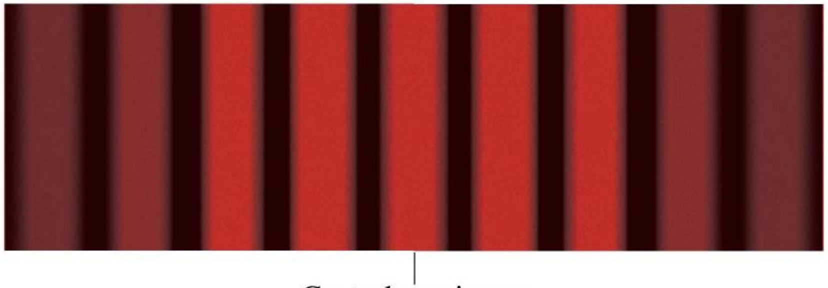
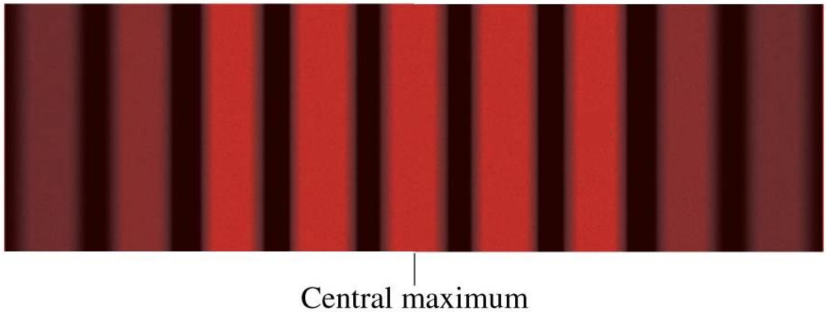


✔ A. Closer together
B. In the same positions.
C. Farther apart.
D. There will be no fringes because the conditions for interference won't be satisfied.

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

QuickCheck 17.5

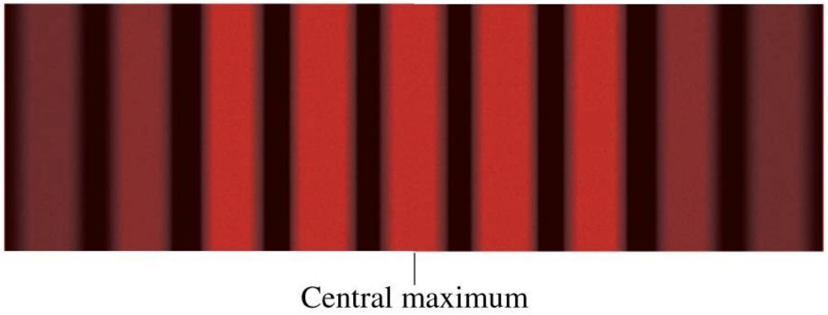
A laboratory experiment produces a double-slit interference pattern on a screen. If the slits are moved closer together, the bright fringes will be



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.

QuickCheck 17.5

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.

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

Example 17.3 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. From the center of one particular fringe to the center of the ninth bright fringe from this one is 1.6 cm. What is the wavelength of the light?

Example 17.3 Measuring the wavelength of light (cont.)

PREPARE 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, expressed in Equation 17.9, that the fringe spacing Δy is uniform. The interference pattern looks like the photograph of Figure 17.6b.

Example 17.3 Measuring the wavelength of light (cont.)

SOLVE The fringe spacing is

$$\Delta y = \frac{1.6\text{ cm}}{9} = 1.78 \times 10^{-3}\text{ m}$$

Using this fringe spacing in Equation 17.9, we find that the wavelength is

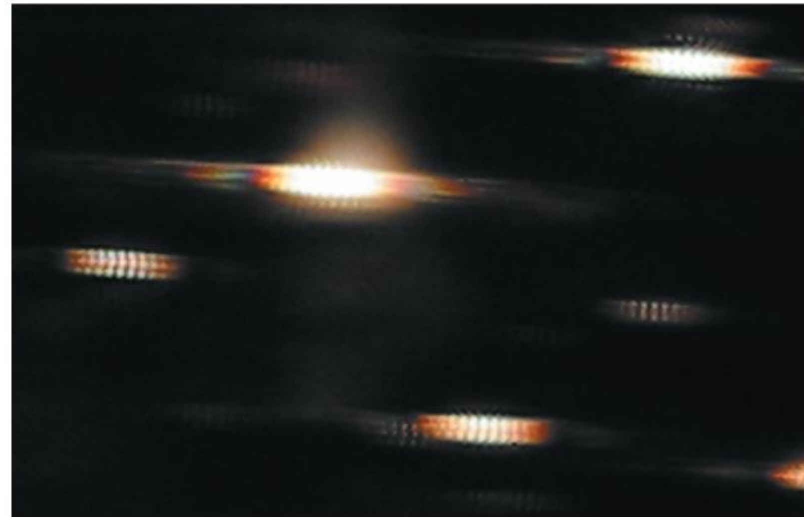
$$\lambda = \frac{d}{L}\Delta y = \frac{3.0 \times 10^{-4}\text{ m}}{1.0\text{ m}}(1.78 \times 10^{-3}\text{ m})$$
$$= 5.3 \times 10^{-7}\text{ m} = 530\text{ nm}$$

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

Example 17.3 Measuring the wavelength of light (cont.)

ASSESS You learned in Chapter 15 that visible light spans the wavelength range 400–700 nm, so finding a wavelength in this range is reasonable. In fact, it's because of experiments like the double-slit experiment that we're able to measure the wavelengths of light.

Try It Yourself: Observing Interference



It's actually not that hard to observe double-slit interference. Place a piece of aluminum foil on a hard surface and cut two parallel slits, about 1 mm apart, using a razor blade. Now hold the slits up to your eye and look at a distant small bright light, such as a streetlight at night. Because of diffraction, you'll see the light source spread out in a direction *perpendicular* to the long direction of the slits. Superimposed on the diffraction pattern is a fine pattern of interference maxima and minima, as seen in the photo above of Christmas tree lights taken through two slits in foil.

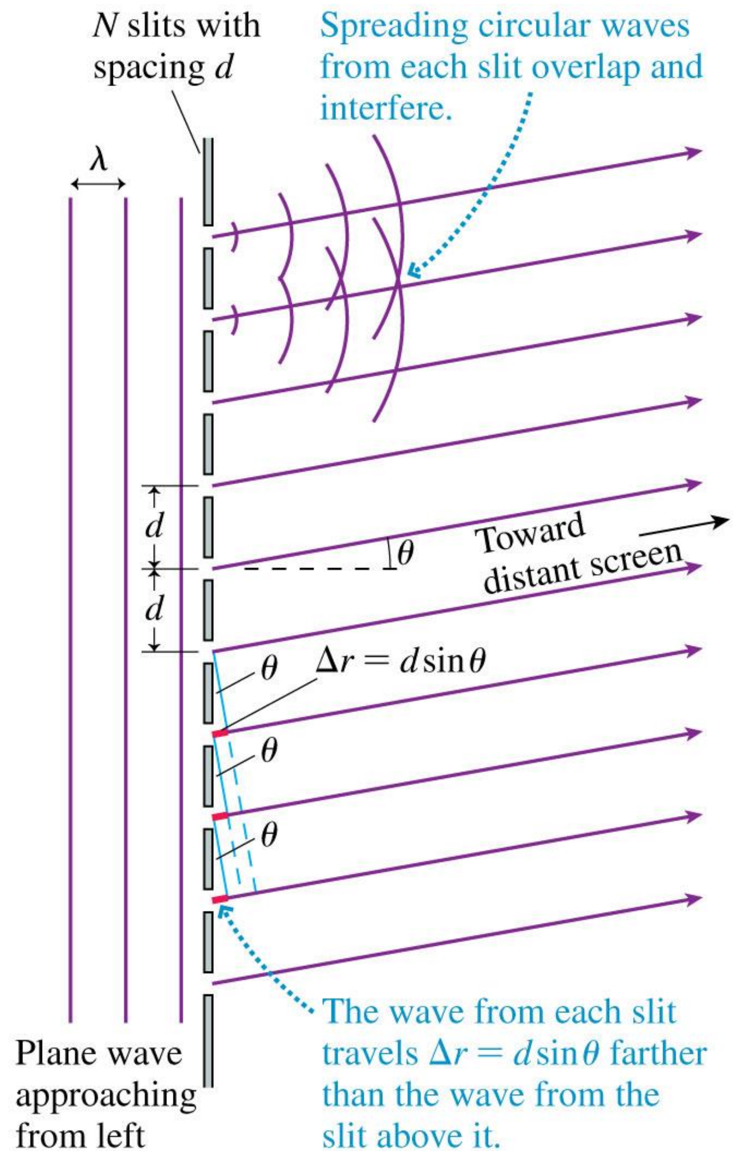
Example Problem

Two narrow slits 0.04 mm apart are illuminated by light from a HeNe laser (λ = 633 nm). What is the angle of the first (m = 1) bright fringe? What is the angle of the 30th bright fringe?

Section 17.3 The Diffraction Grating

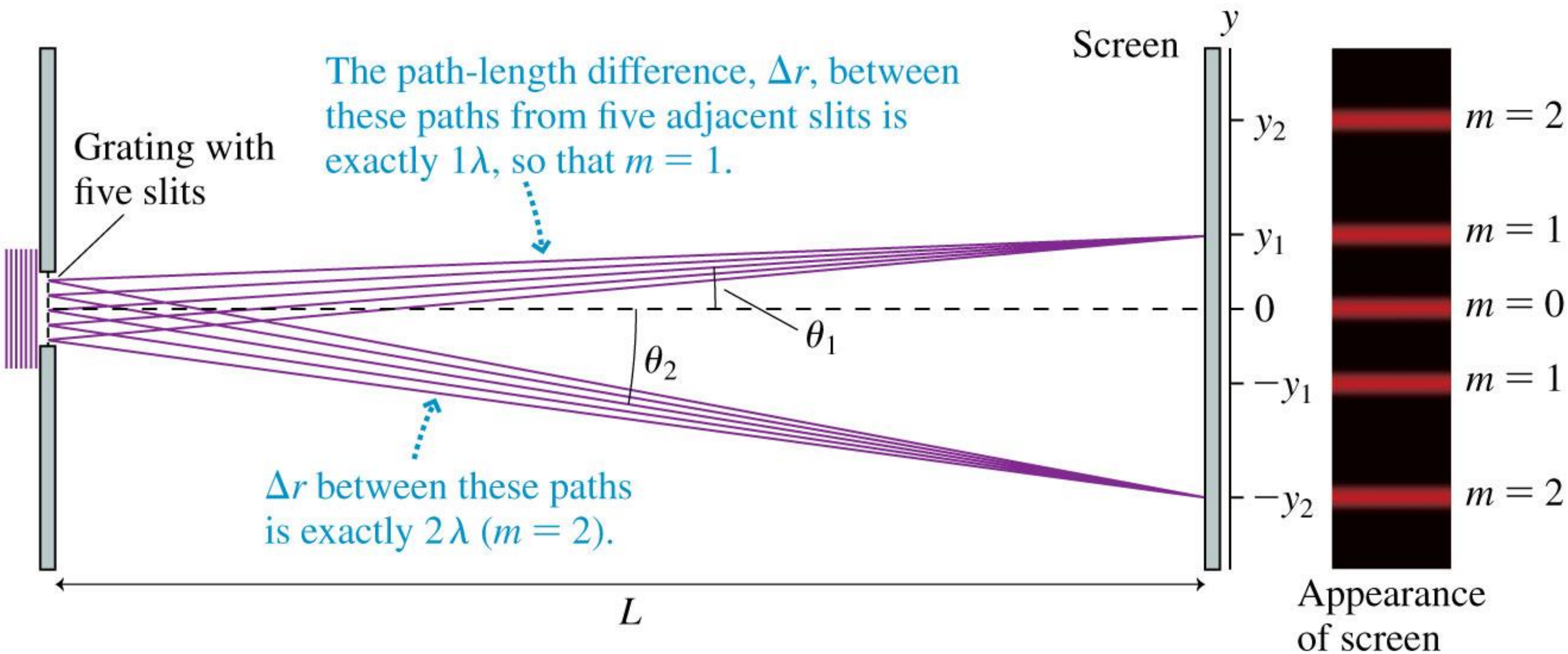
The Diffraction Grating

- A **diffraction grating** is a multi-slit device.
- The waves emerge from each slit *in phase*.
- Each wave will spread out and interfere with each other wave.
- The distance the wave travels from one slit is farther than from the wave above it, and less than the wave below it in this figure.



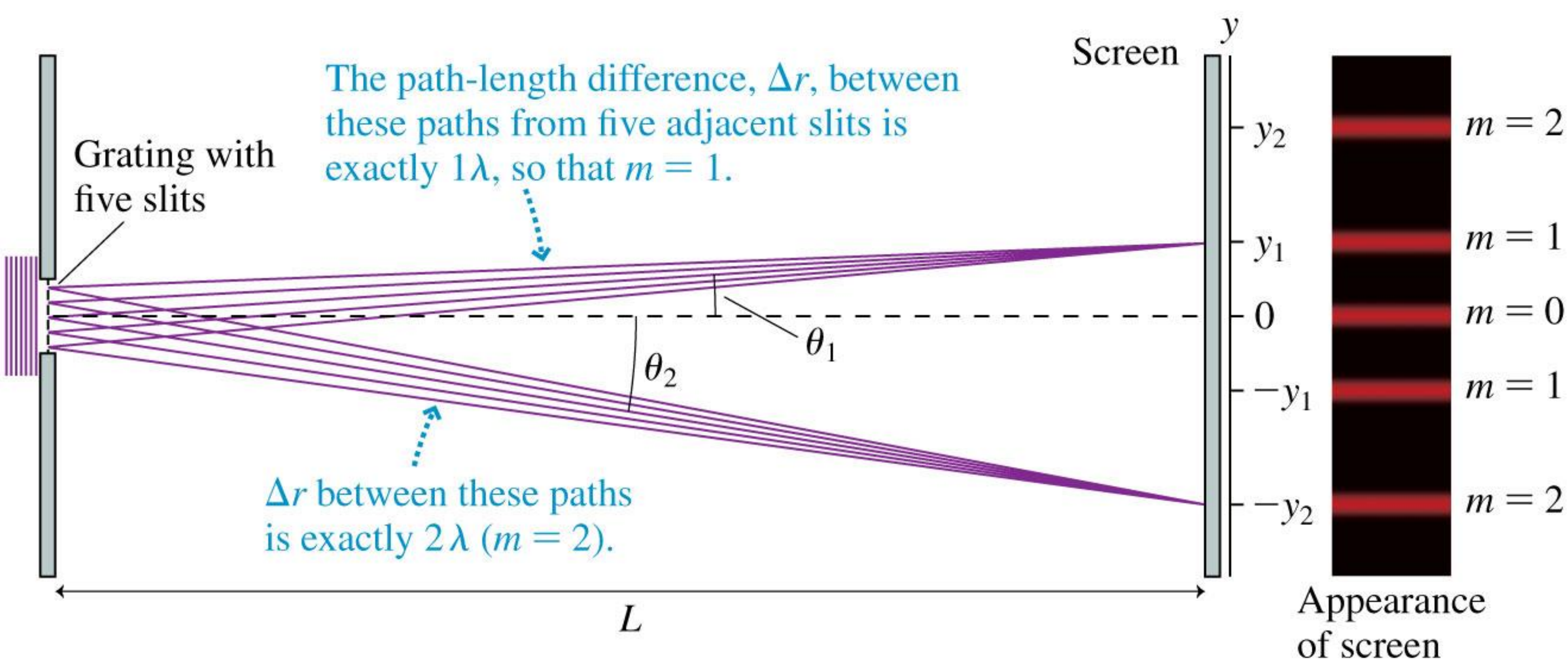
The Diffraction Grating

- Assuming L is much larger than d, the paths followed by the light from slits to a point on the screen are *very nearly* parallel.



The Diffraction Grating

- If the angle is such that $\Delta r = d\sin\theta_m = m\lambda$, then the light wave arriving at the screen from one slit will travel exactly m wavelengths more or less than light from the two slits next to it. So the waves are exactly in phase.



The Diffraction Grating

- **N light waves, from N different slits, will *all* be in phase with each other when they arrive at a point on the screen at angle θ_m such that**

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

Angles of bright fringes due to a diffraction grating with slits distance d apart

- The position y_m of the mth maximum is

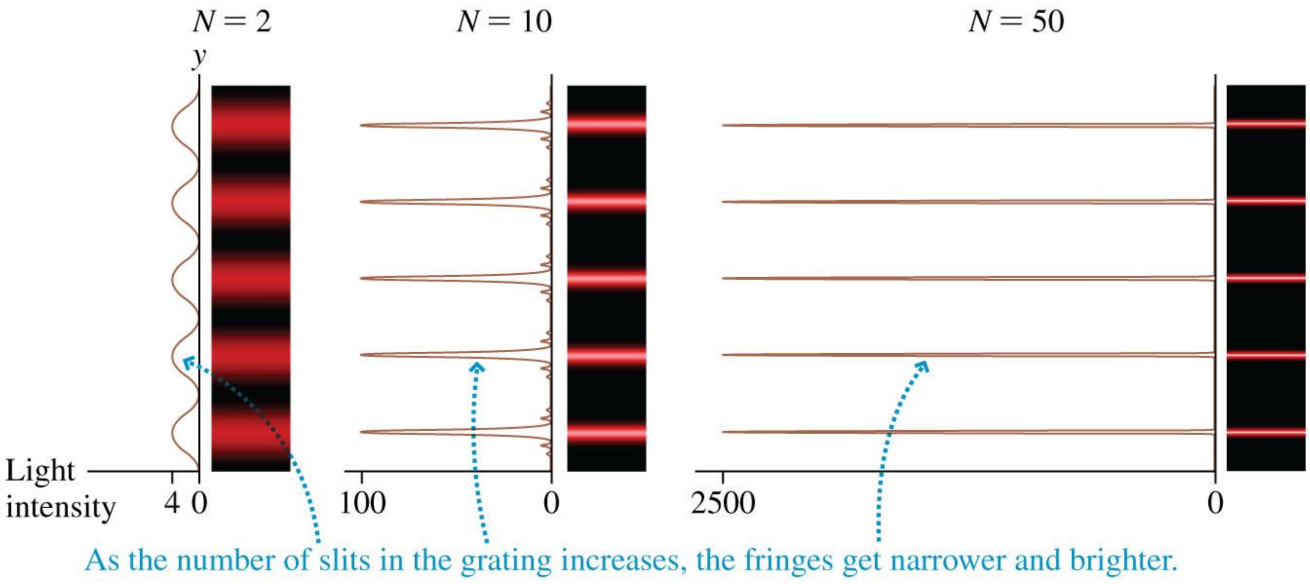
$$y_m = L \tan\theta_m$$

Positions of bright fringes due to a diffraction grating distance L from screen

- The integer m is called the **order** of diffraction.

The Diffraction Grating

- There is an important difference between the intensity pattern of double-slit interference and the intensity pattern of multiple-slit diffraction grating.
- The bright fringes of a diffraction grating are *much* narrower. As the number of slits, *N*, increases, the bright fringes get narrower and brighter.



QuickCheck 17.6

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 17.6

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

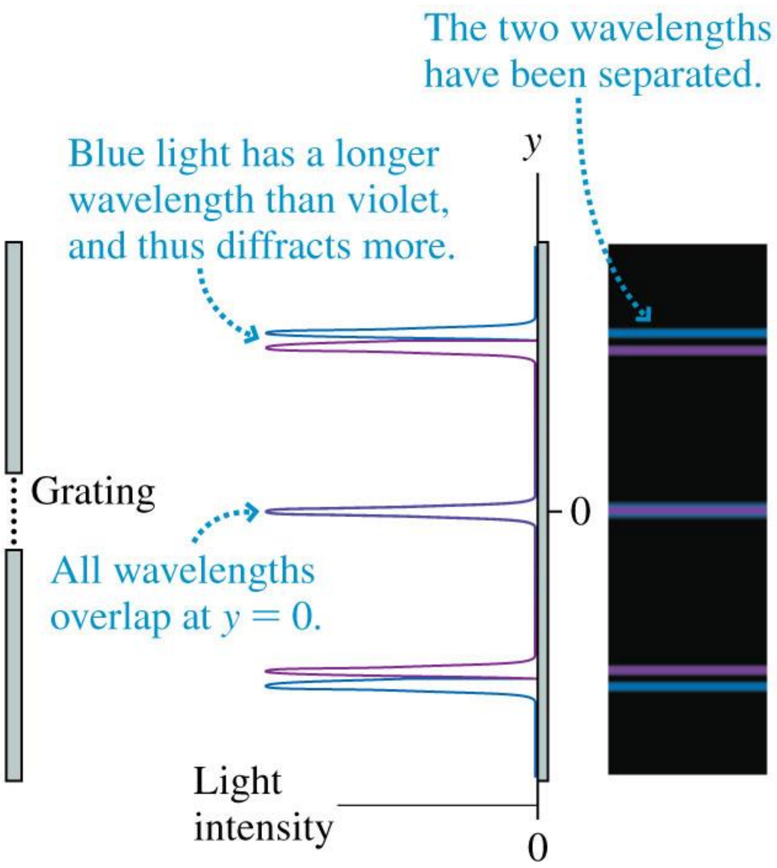
A. The fringes stay the same brightness and get closer together.
B. The fringes stay the same brightness and get farther apart.
✔ C. The fringes stay in the same positions but get brighter and narrower.
D. The fringes stay in the same positions but get dimmer and wider.
E. The fringes get brighter, narrower,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

Spectroscopy

- **Spectroscopy** is the science of measuring the wavelengths of atomic and molecular emissions.
- Atomic elements in the periodic table emit light at certain, well-defined wavelengths when excited by light, electricity, or collisions.
- Because their bright fringes are distinct, diffraction gratings are an ideal tool for spectroscopy.

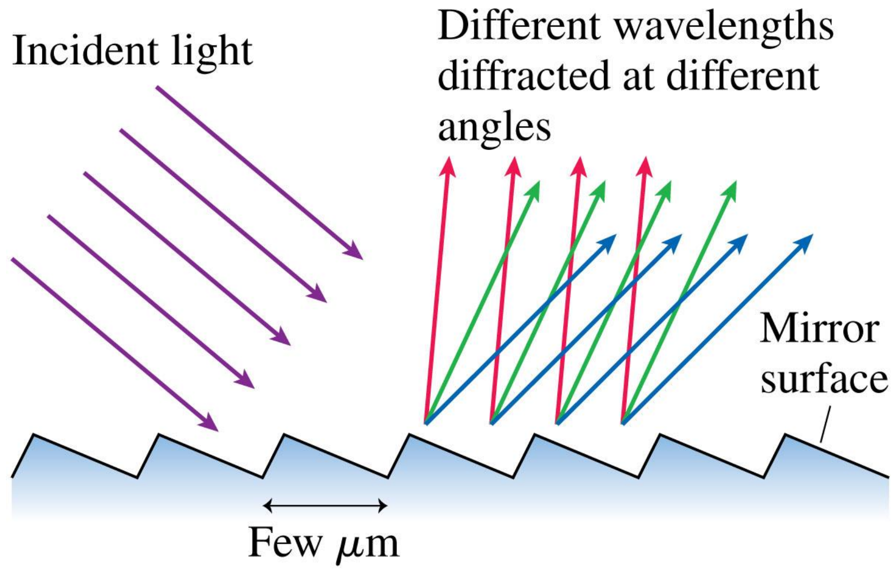
Spectroscopy

- If the light incident on a grating consists of two slightly different wavelengths, they will diffract at slightly different angles.
- If N is sufficiently large, two distinct fringes will appear on the screen.



Reflection Gratings

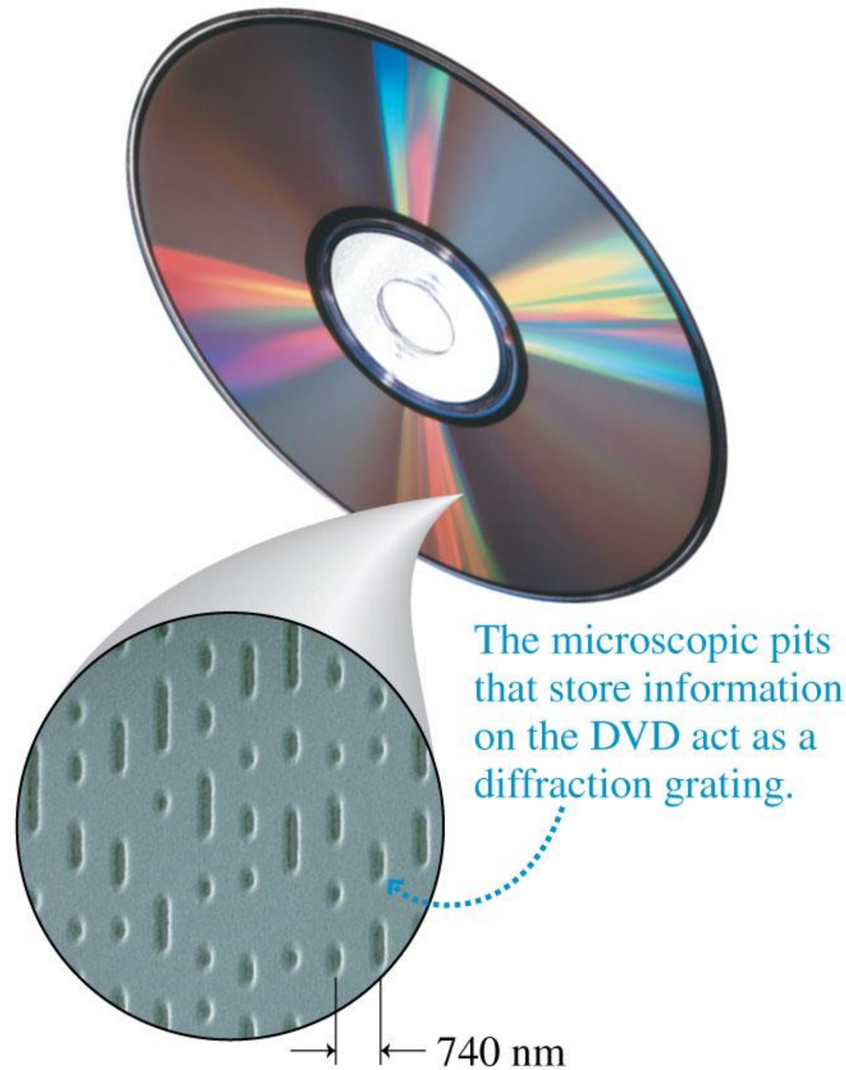
- It is more practical to make *reflection gratings*, like a mirror with hundreds or thousands of narrow grooves cut into the surface.
- The grooves divide the surface into many parallel reflective stripes, which spread the wave.



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.

Reflection Gratings

- The interference pattern is exactly the same as the pattern of light transmitted through *N* parallel slits.
- The calculations determined for the diffraction grating **applies to reflection gratings as well as to transmission gratings.**
- The array of holes on a DVD is used to transmit data, but optically they cause the rainbow colors observed.



Reflection Gratings

SYNTHESIS 17.1 Double-slit interference and diffraction gratings

The physical principles underlying double-slit interference and diffraction gratings are the same: A bright fringe occurs on a screen when the path-length difference between waves is an integer number $m = 0, 1, 2, 3 \ldots$ times the wavelength λ.

Double-slit interference

Wavelength (m)

Distance between slits (m)

$$\theta_m = m\frac{\lambda}{d}$$

Distance to screen (m)

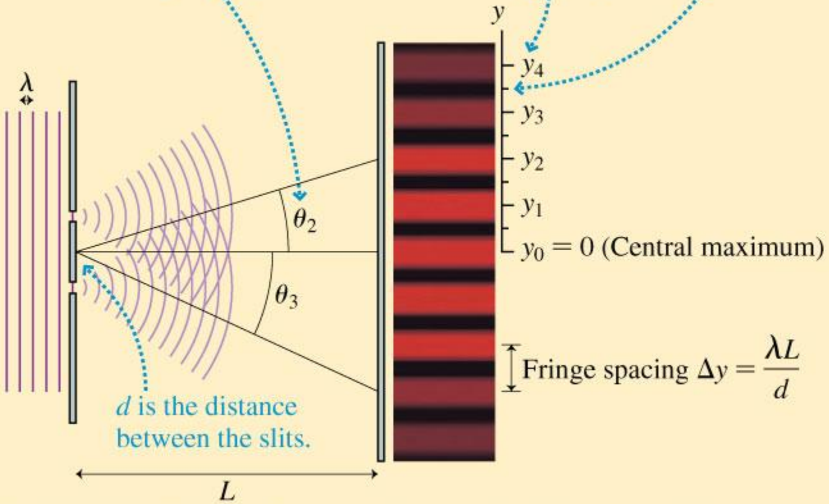
$$y_m = \frac{m\lambda L}{d}$$

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

θ_m is the angle *in radians* of the mth bright fringe.

y_m is the position of the mth bright fringe.

y'_m is the position of the mth dark fringe.



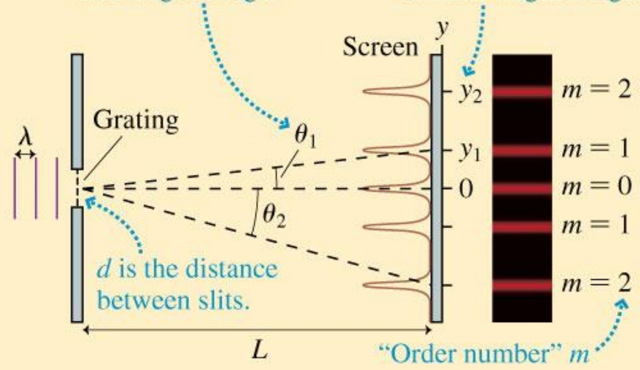
In double-slit interference, the angles θ are usually very small and we can use the small-angle approximation in the equations.

Diffraction gratings

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

θ_m is the angle of the mth bright fringe.

y_m is the position of the mth bright fringe.



For a diffraction grating, the small-angle approximation is generally not valid. To find the bright-fringe positions y_m, you must first find the angle θ_m from $d\sin\theta_m = m\lambda$, then use $y_m = L\tan\theta_m$.

A grating with N slits or lines per mm has slit spacing $d = (1 \text{ mm})/N$.

Text: p. 547

Section 17.4 Thin-Film Interference

Thin-Film Interference

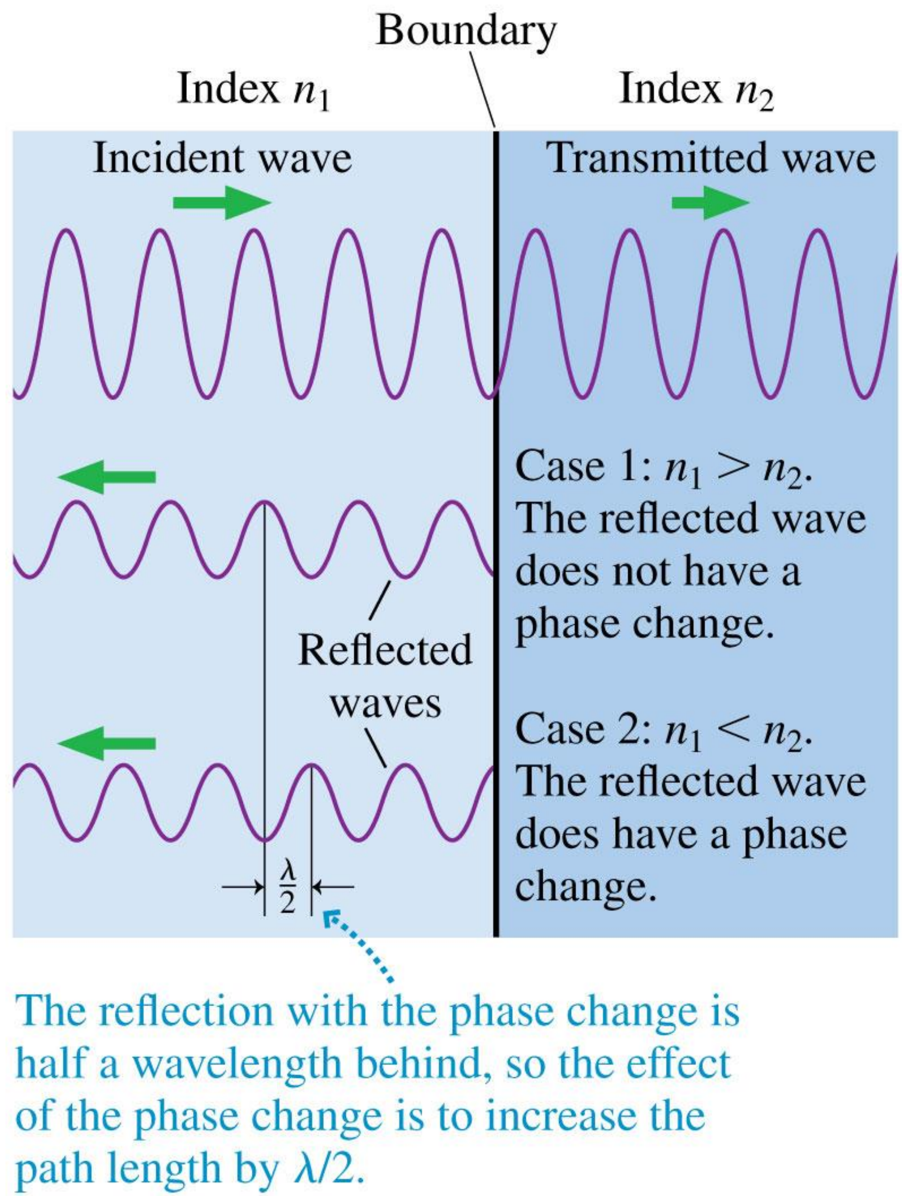
- **Thin-film interference** is the interference of light waves reflected from two boundaries of a thin film.
- Thin-films are used for antireflection coatings on camera lenses, microscopes, and other optical equipment. The bright colors of oil slicks and soap bubbles are also due to thin-film interference.

Interference of Reflected Light Waves

- A light wave is partially reflected from *any* boundary between two transparent media with different indices of refraction.
- The light is partially reflected not only from the front surface of a sheet of glass, but also from the back surface as it exits the glass into air. This leads to *two* reflections.

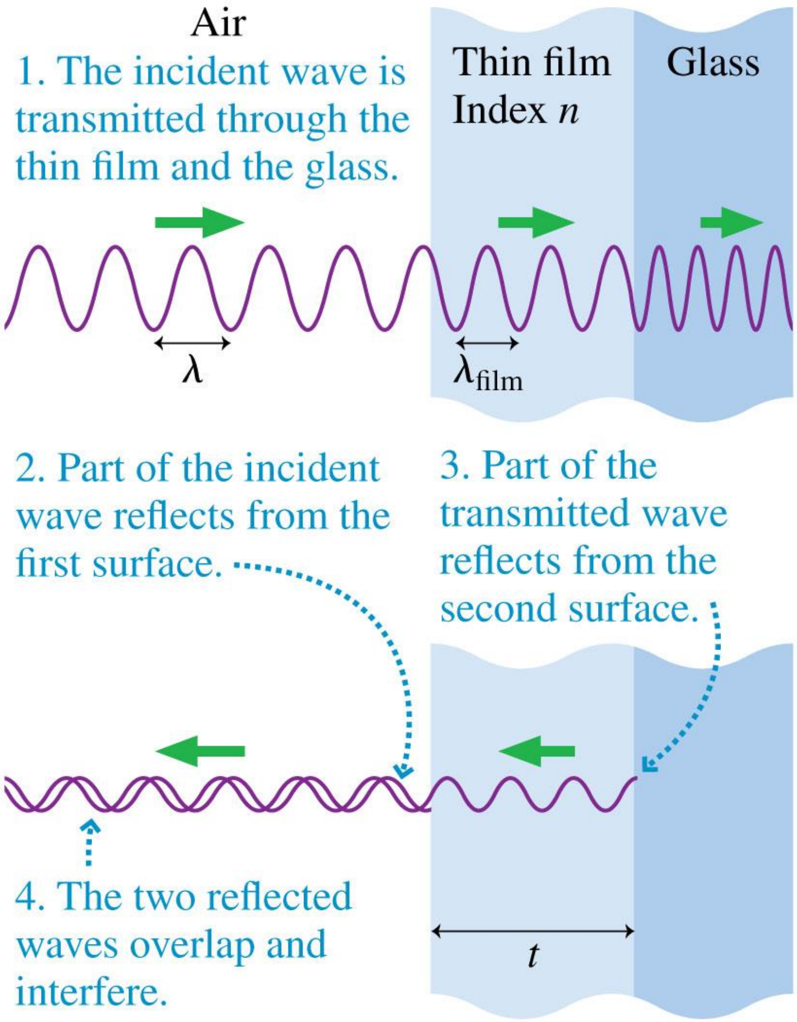
Interference of Reflected Light Waves

- **A light wave undergoes a phase change if it reflects from a boundary at which the index of refraction increases.**
- There is no phase change at a boundary where the index of refraction decreases.



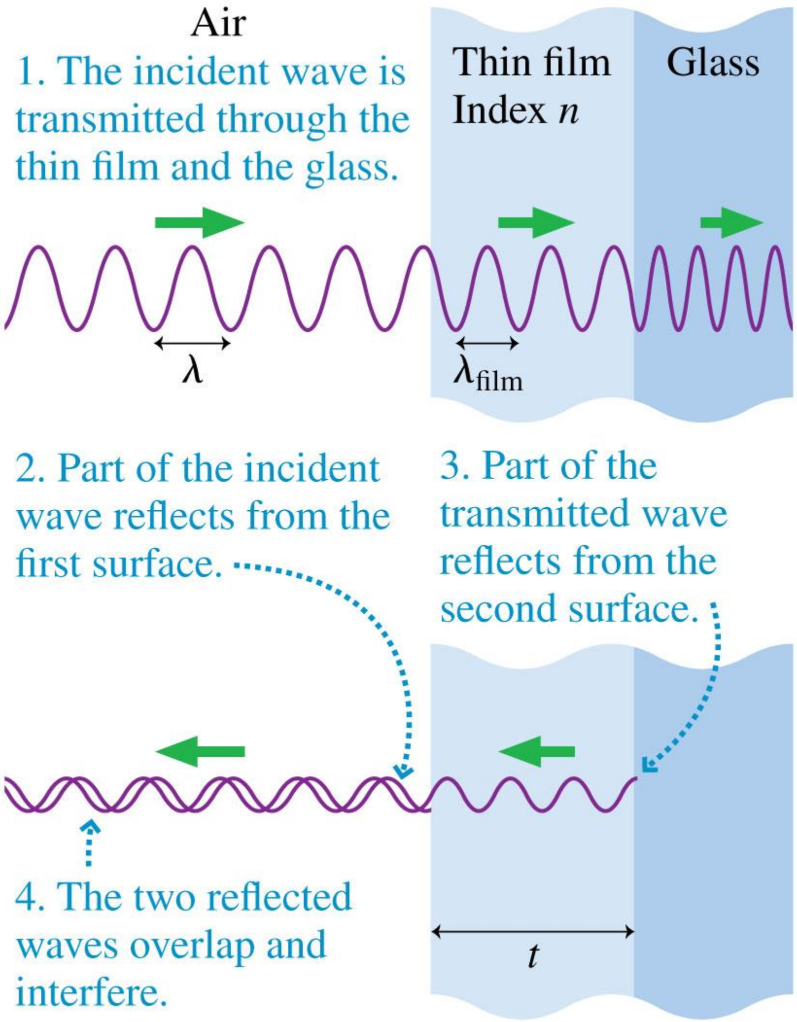
Interference of Reflected Light Waves

- For a thin, transparent film, most of the light is transmitted into the film. Some light is reflected off the first (air-film) boundary, and some is later reflected at the second (film-glass) boundary.
- The two reflected waves will interfere.



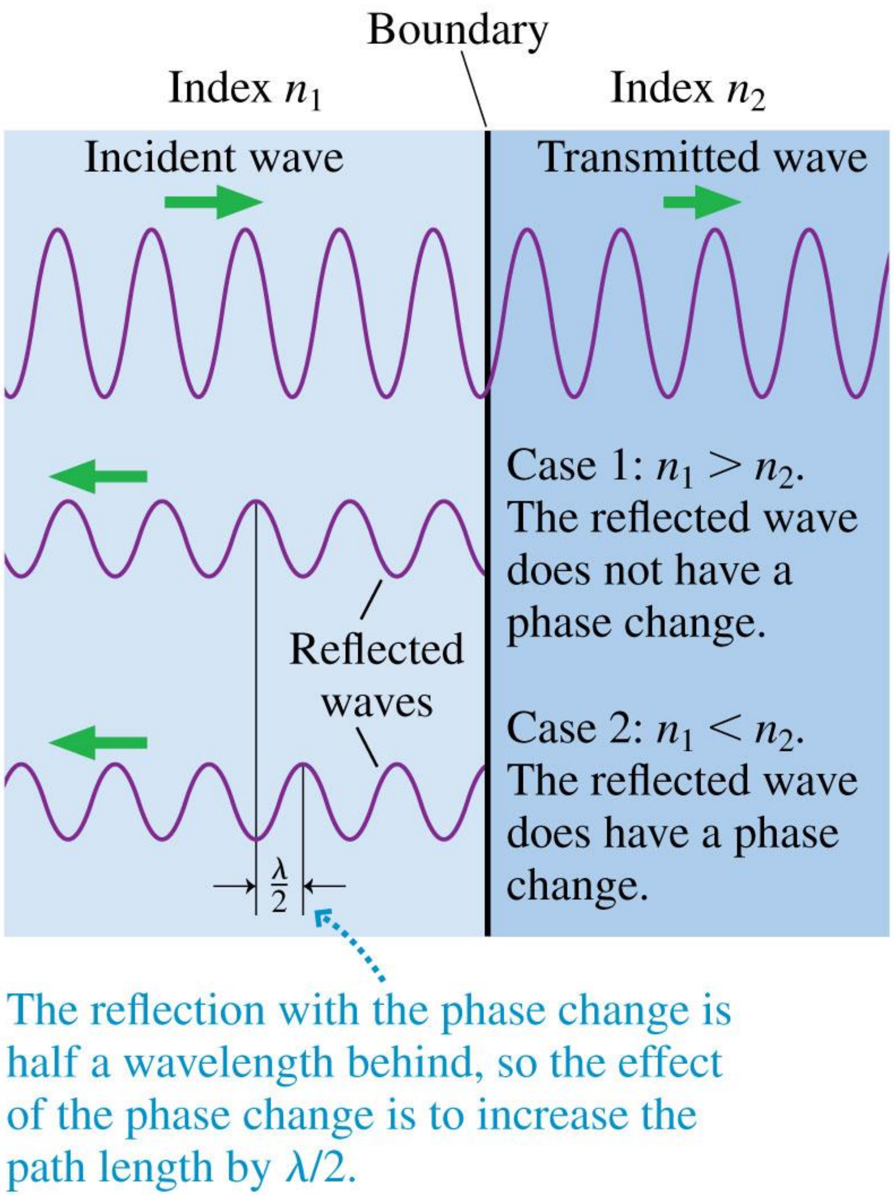
Interference of Reflected Light Waves

- If the waves are *in phase* they will interfere constructively and cause a *strong reflection.*
- If they are *out of phase* they will interfere destructively and cause a *weak reflection*, or *no reflection* at all.



Interference of Reflected Light Waves

- The path-length difference of the reflected waves is $\Delta d = 2t$ because the second wave travels through the film of thickness t twice.
- The phase change that occurs when a light wave reflects from a boundary with a higher index of refraction is equivalent to adding an extra half-wavelength to the distance traveled.



Interference of Reflected Light Waves

The possible phase change leads to two situations:

1. If *neither* or *both* waves have a phase change due to reflection, the net addition to the path-length difference is zero. The *effective path-length difference* is $\Delta d_{\text{eff}} = 2t$.
2. If only *one* wave has a phase change due to the reflection, the effective path-length difference is increased by one half-wavelength to $\Delta d_{\text{eff}} = 2t + \frac{1}{2}\lambda$.

Interference of Reflected Light Waves

- The conditions for constructive and destructive interference of the light waves reflected by a thin film are

$$2t = m\frac{\lambda}{n} \qquad m = 0, 1, 2, \ldots$$

Condition for constructive interference with either 0 or 2 reflective phase changes

Condition for destructive interference with only 1 reflective phase change

$$2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n} \qquad m = 0, 1, 2, \ldots$$

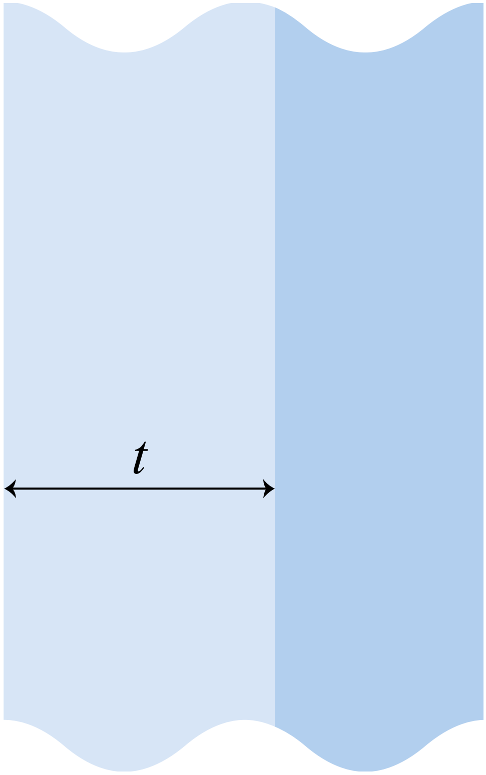
Condition for destructive interference with either 0 or 2 reflective phase changes

Condition for constructive interference with only 1 reflective phase change

QuickCheck 17.7

A film with thickness *t* gives constructive interference for light with a wavelength in the film of λ_{film}. How much thicker would the film need to be in order to give destructive interference?

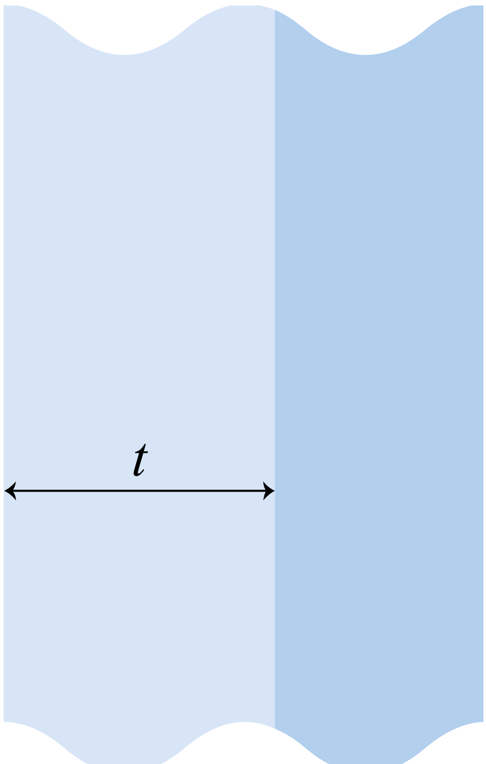
A. $2\lambda_{\text{film}}$
B. λ_{film}
C. $\lambda_{\text{film}}/2$
D. $\lambda_{\text{film}}/4$



QuickCheck 17.7

A film with thickness t gives constructive interference for light with a wavelength in the film of λ_{film}. How much thicker would the film need to be in order to give destructive interference?

A. $2\lambda_{\text{film}}$
B. λ_{film}
C. $\lambda_{\text{film}}/2$
✔ D. $\lambda_{\text{film}}/4$



QuickCheck 17.8

A film of oil (index of refraction $n_{oil} = 1.2$) floats on top of an unknown fluid X (with unknown index of refraction n_X). The thickness of the oil film is known to be very small, on the order of 10 nm. A beam of white light illuminates the oil from the top, and you observe that there is very little reflected light, much less reflection than at an interface between air and X. What can you say about the index of refraction of X?

A. $n_X > 1.2$
B. $n_X = 1.2$
C. $n_X < 1.2$
D. There is insufficient information to choose any of the above.

QuickCheck 17.8

A film of oil (index of refraction $n_{\text{oil}} = 1.2$) floats on top of an unknown fluid X (with unknown index of refraction n_X). The thickness of the oil film is known to be very small, on the order of 10 nm. A beam of white light illuminates the oil from the top, and you observe that there is very little reflected light, much less reflection than at an interface between air and X. What can you say about the index of refraction of X?

✔ A. $n_X > 1.2$
B. $n_X = 1.2$
C. $n_X < 1.2$
D. There is insufficient information to choose any of the above.

Interference of Reflected Light Waves

TACTICS BOX 17.1 **Analyzing thin-film interference**

Follow the light wave as it passes through the film. The wave reflecting from the second boundary travels an extra distance $2t$.

1. Note the indices of refraction of the three media: the medium before the film, the film itself, and the medium beyond the film. The first and third may be the same. There's a reflective phase change at any boundary where the index of refraction increases.
2. If *neither* or *both* reflected waves undergo a phase change, the phase changes cancel and the effective path-length difference is $\Delta d = 2t$. Use Equation 17.14 for constructive interference and 17.15 for destructive interference.
3. If *only one* wave undergoes a phase change, the effective path-length difference is $\Delta d = 2t + \frac{1}{2}\lambda$. Use Equation 17.14 for destructive interference and 17.15 for constructive interference.

Exercises 12, 13

Text: p. 549

Example 17.5 Designing an antireflection coating

To keep unwanted light from reflecting from the surface of eyeglasses or other lenses, a thin film of a material with an index of refraction $n = 1.38$ is coated onto the plastic lens ($n = 1.55$). It is desired to have destructive interference for $\lambda = 550$ nm because that is the center of the visible spectrum. What is the thinnest film that will do this?

Example 17.5 Designing an antireflection coating (cont.)

PREPARE We follow the steps of Tactics Box 17.1. As the light traverses the film, it first reflects at the front surface of the coating. Here, the index of refraction increases from that of air ($n = 1.00$) to that of the film ($n = 1.38$), so there will be a reflective phase change. The light then reflects from the rear surface of the coating. The index again increases from that of the film ($n = 1.38$) to that of the plastic ($n = 1.55$). With two phase changes, Tactics Box 17.1 tells us that we should use Equation 17.15 for destructive interference.

Example 17.5 Designing an antireflection coating (cont.)

SOLVE We can solve Equation 17.15 for the thickness t that causes destructive interference:

$$t = \frac{\lambda}{2n}\left(m + \frac{1}{2}\right)$$

The thinnest film is the one for which $m = 0$, giving

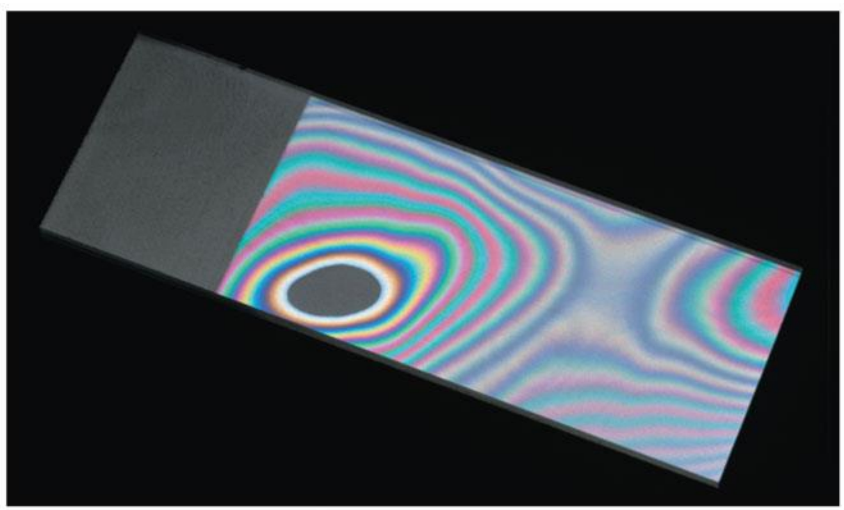
$$t = \frac{550\text{ nm}}{2(1.38)} \times \frac{1}{2} = 100\text{ nm}$$

Example 17.5 Designing an antireflection coating (cont.)

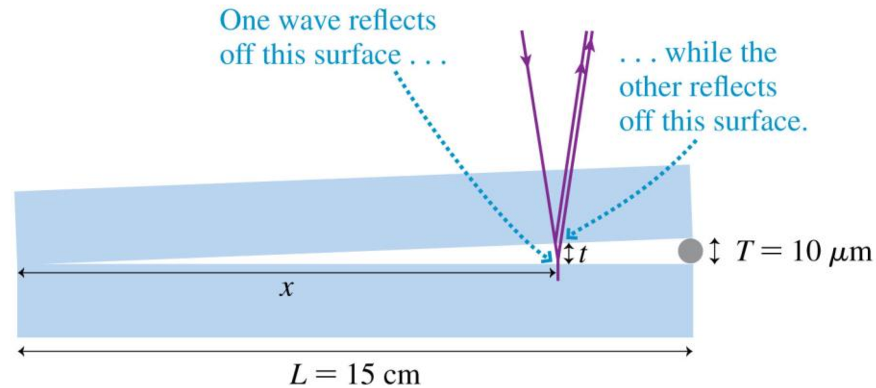
ASSESS Interference effects occur when path-length differences are on the order of a wavelength, so our answer of 100 nm seems reasonable.

Thin Films of Air

- A film does not need to be a solid material, it can also be air.
- A thin layer of air between two microscope slides pressed together can create light and dark fringes.
- The varying air layer's thickness can cause constructive and destructive interference at different points between the slides.

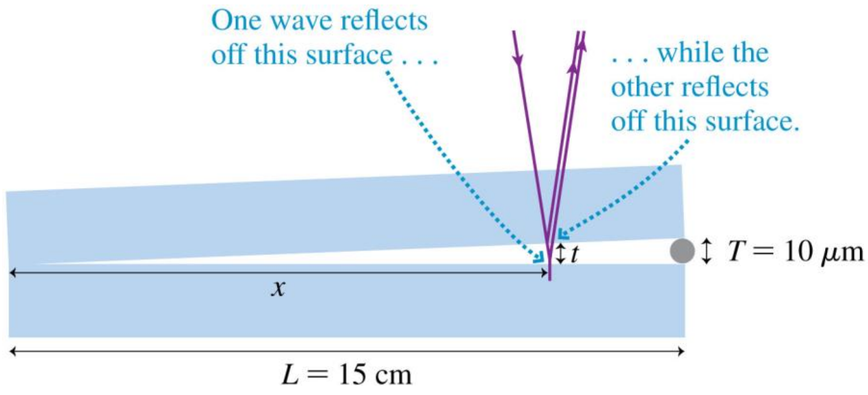


Example 17.6 Finding the fringe spacing from a wedged-shaped film of air



Two 15-cm-long flat glass plates are separated by a 10-μm-thick spacer at one end, leaving a thin wedge of air between them, as shown in FIGURE 17.20. The plates are illuminated by light from a sodium lamp with wavelength $\lambda = 589$ nm. Alternating bright and dark fringes are observed. What is the spacing between two bright fringes?

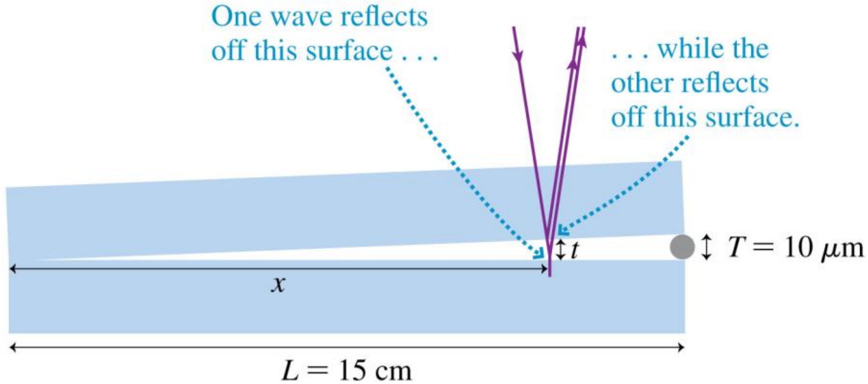
Example 17.6 Finding the fringe spacing from a wedged-shaped film of air (cont.)



PREPARE The wave reflected from the lower plate has a reflective phase change, but the top reflection does not because the index of refraction decreases at the glass-air boundary. According to Tactics Box 17.1, we should use Equation 17.15 for constructive interference:

$$2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$$

Example 17.6 Finding the fringe spacing from a wedged-shaped film of air (cont.)



This is a film of air, so here n is the index of refraction of air. Each integer value of m corresponds to a wedge thickness t for which there is constructive interference and thus a bright fringe.

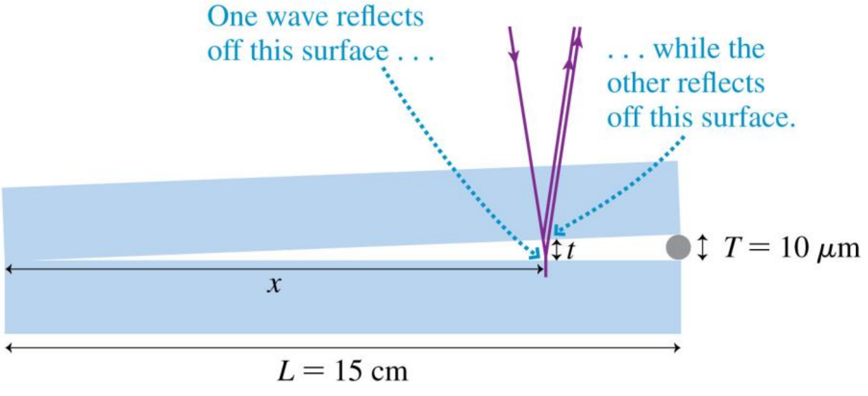
SOLVE Let x be the distance from the left end to a bright fringe. From Figure 17.20, by similar triangles we have

$$\frac{t}{x} = \frac{T}{L}$$

or $t = xT/L$.

Example 17.6 Finding the fringe spacing from a wedged-shaped film of air (cont.)

From the condition for constructive interference, we then have



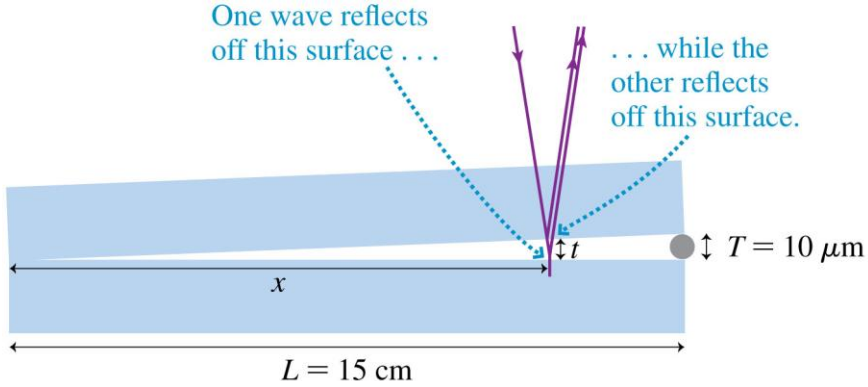
$$2\frac{xT}{L} = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$$

There will be a bright fringe for any integer value of *m*, and so the position of the *m*th fringe, as measured from the left end, is

$$x_m = \frac{\lambda L}{2nT}\left(m + \frac{1}{2}\right)$$

Example 17.6 Finding the fringe spacing from a wedged-shaped film of air (cont.)

We want to know the spacing between two adjacent fringes, m and $m + 1$, which is

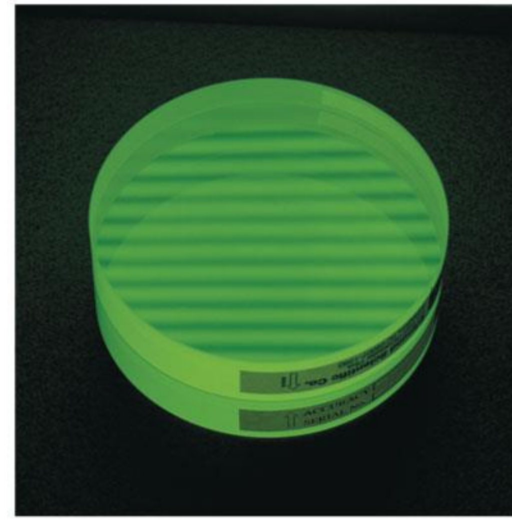


$$\Delta x = x_{m+1} - x_m = \frac{\lambda L}{2nT}\left(m + 1 + \frac{1}{2}\right) - \frac{\lambda L}{2nT}\left(m + \frac{1}{2}\right) = \frac{\lambda L}{2nT}$$

Evaluating, we find

$$\Delta x = \frac{\lambda L}{2nT} = \frac{(5.89 \times 10^{-7}\ \text{m})(0.15\ \text{m})}{2(1.00)(10 \times 10^{-6}\ \text{m})} = 4.4\ \text{mm}$$

Example 17.6 Finding the fringe spacing from a wedged-shaped film of air (cont.)



ASSESS As the photo shows, if the two plates are very flat, the fringes will appear as straight lines perpendicular to the direction of increasing air thickness. However, if the plates are not quite flat, the fringes will appear curved. The amount of curvature indicates the departure of the plates from perfect flatness.

The Colors of Soap Bubbles and Oil Slicks

- The bright colors of soap bubbles or oil slicks on water are due to thin-film interference of white light, or a mixture of *all* wavelengths, rather than just one wavelength of light.
- For a soap bubble, the light reflecting at the front surface of the bubble (the air-water boundary) undergoes a phase change, but the back reflection does not.

The Colors of Soap Bubbles and Oil Slicks

- For a 470-nm thick-soap bubble, light near the ends of the spectrum undergoes destructive interference while light at the middle of the spectrum (green) undergoes constructive interference and is strongly reflected.
- Soap film of this thickness will therefore appear green.

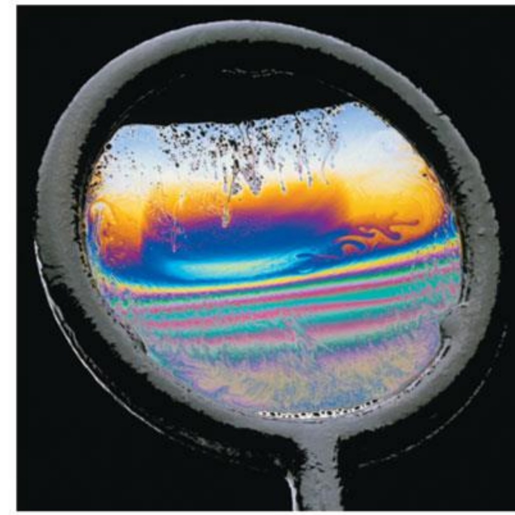
TABLE 17.2 Wavelengths for constructive and destructive interference from a 470-nm-thick soap bubble. Visible wavelengths are shown in **bold.**

Equation	$m = 1$	$m = 2$	$m = 3$
$\lambda_{\text{con}} = \dfrac{2nt}{m + \frac{1}{2}}$	833 nm	**500 nm**	357 nm
$\lambda_{\text{des}} = \dfrac{2nt}{m}$	1250 nm	**625 nm**	**417 nm**

Conceptual Example 17.7 Colors in a vertical soap film

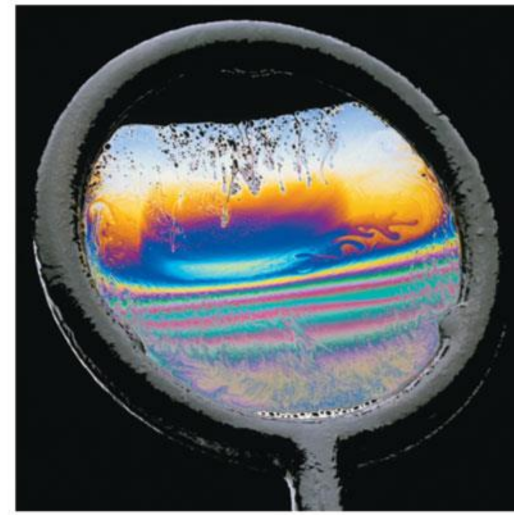
FIGURE 17.22 shows a soap film in a metal ring. The ring is held vertically. Explain the colors seen in the film.

Conceptual Example 17.7 Colors in a vertical soap film (cont.)



REASON Because of gravity, the film is thicker near the bottom and thinner at the top. It thus has a wedge shape, and the interference pattern consists of lines of alternating constructive and destructive interference, just as for the air wedge of Example 17.6. Because this soap film is illuminated by white light, colors form as just discussed for any soap film.

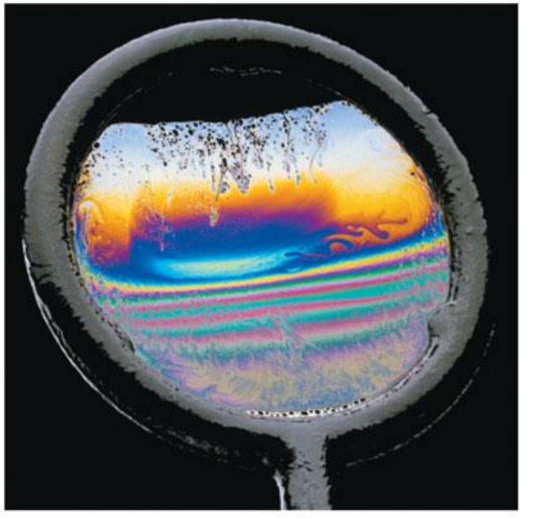
Conceptual Example 17.7 Colors in a vertical soap film (cont.)



Notice that the very top of the film, which is extremely thin, appears black. This means that it is reflecting no light at all. When the film is very thin—much thinner than the wavelength of light—there is almost no path-length difference between the two waves reflected off the front and the back of the film.

Conceptual Example 17.7 Colors in a vertical soap film (cont.)

However, the wave reflected off the back undergoes a reflective phase change and is out of phase with the wave reflected off the front. The two waves thus *always* interfere destructively, no matter what their wavelength.

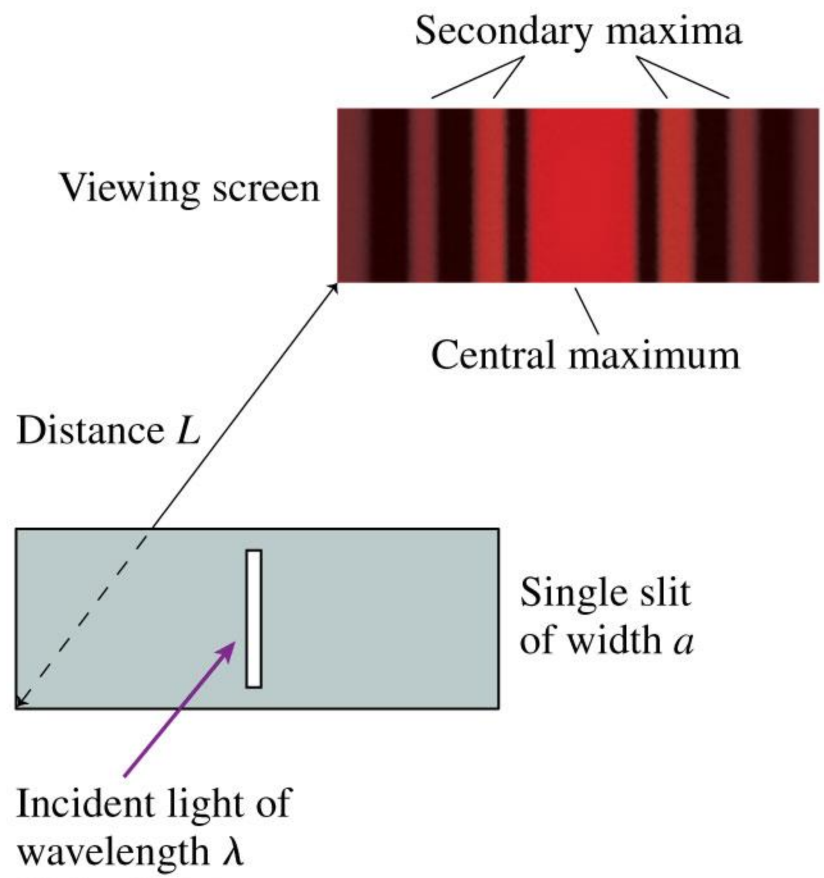


ASSESS This simple experiment shows directly that the two reflected waves have different reflective phase changes.

Section 17.5 Single-Slit Diffraction

Single-Slit Diffraction

- **Single-slit diffraction** is diffraction through a tall, narrow slit of width *a*.
- The light pattern on the viewing screen consists of a *central maximum* and a series of weaker **secondary maxima** and dark fringes.
- The central maximum is much broader and brighter than the secondary maxima.



Huygens' Principle

- To understand diffraction, we need to think about the propagation of an *extended* wave front.
- The Dutch scientist Christiaan Huygens developed a geometrical model to visualize how *any* wave, such as a wave passing through a narrow slit, evolves.

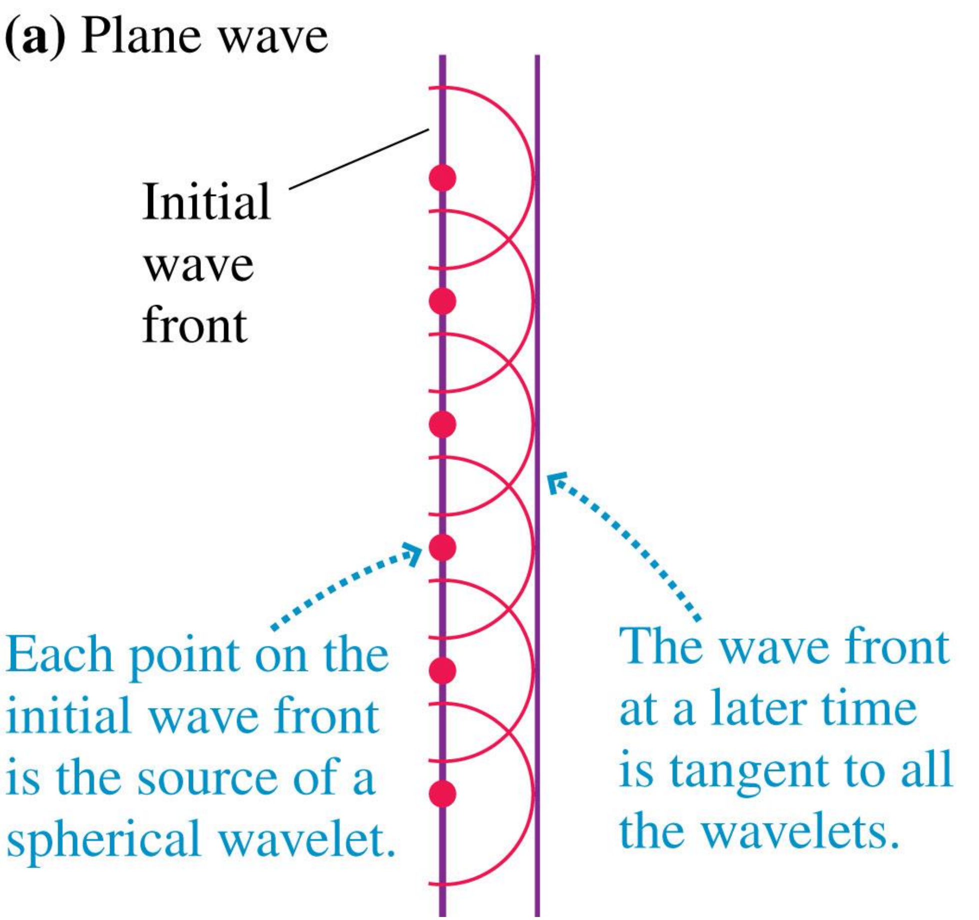
Huygens' Principle

Huygens' Principle has two parts:

1. Each point on a wave front is the source of a spherical *wavelet* that spreads out at the wave speed.
2. At a later time, the shape of the wave front is the curve that is tangent to all the wavelets.

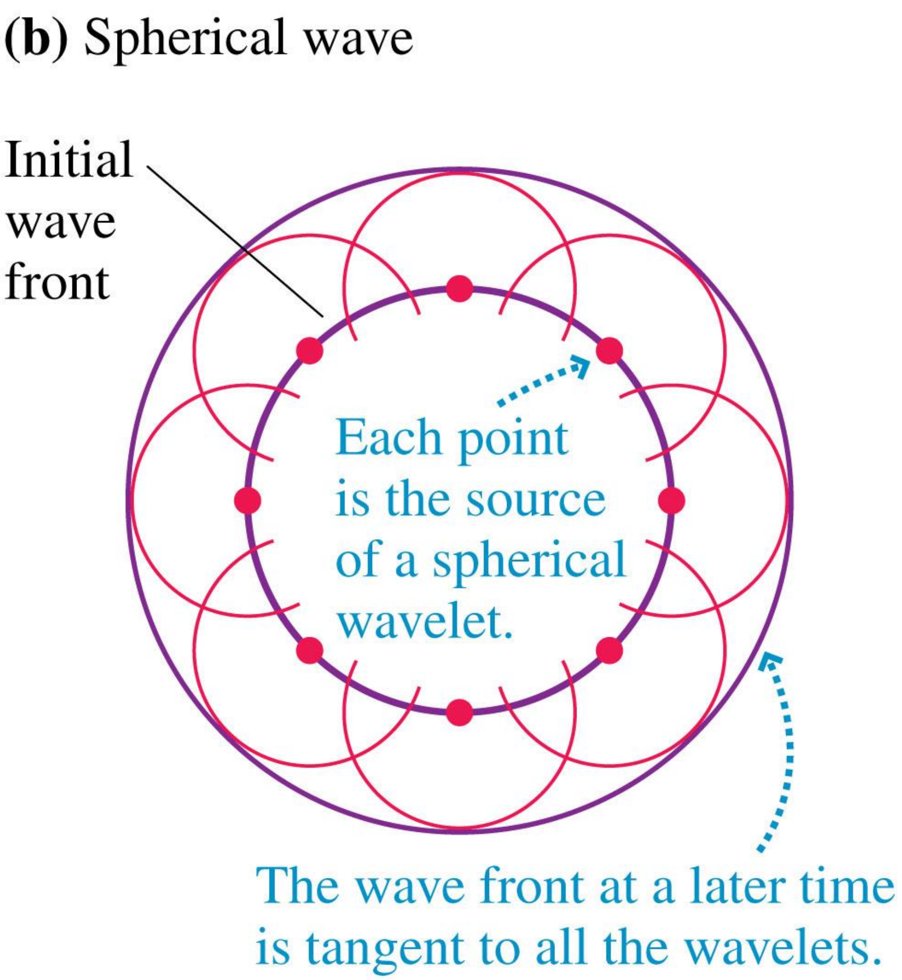
Huygens' Principle

- The curve tangent to the wavelets of a plane wave is a plane that has propagated to the right.



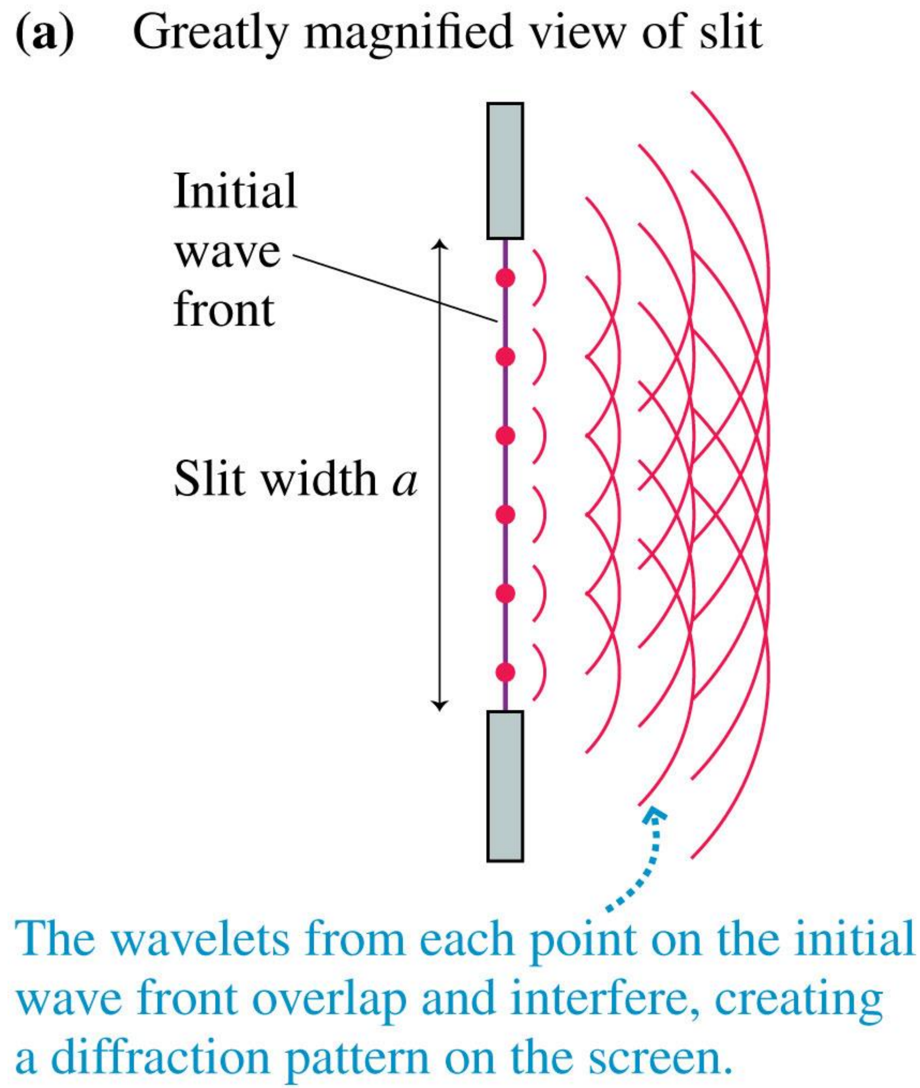
Huygens' Principle

- The curve tangent to the wavelets of a spherical wave is a larger sphere.



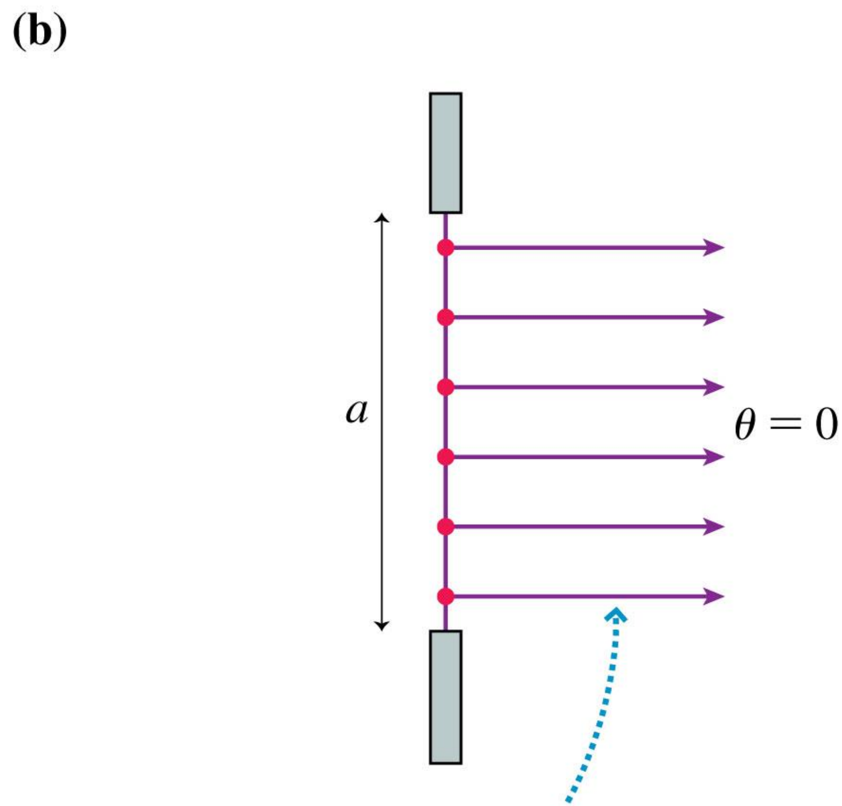
Analyzing Single-Slit Diffraction

- According to Huygens' Principle, each point on the wave front can be thought of as the source of a spherical wavelet.
- These wavelets overlap and interfere producing the diffraction pattern seen on the viewing screen.



Analyzing Single-Slit Diffraction

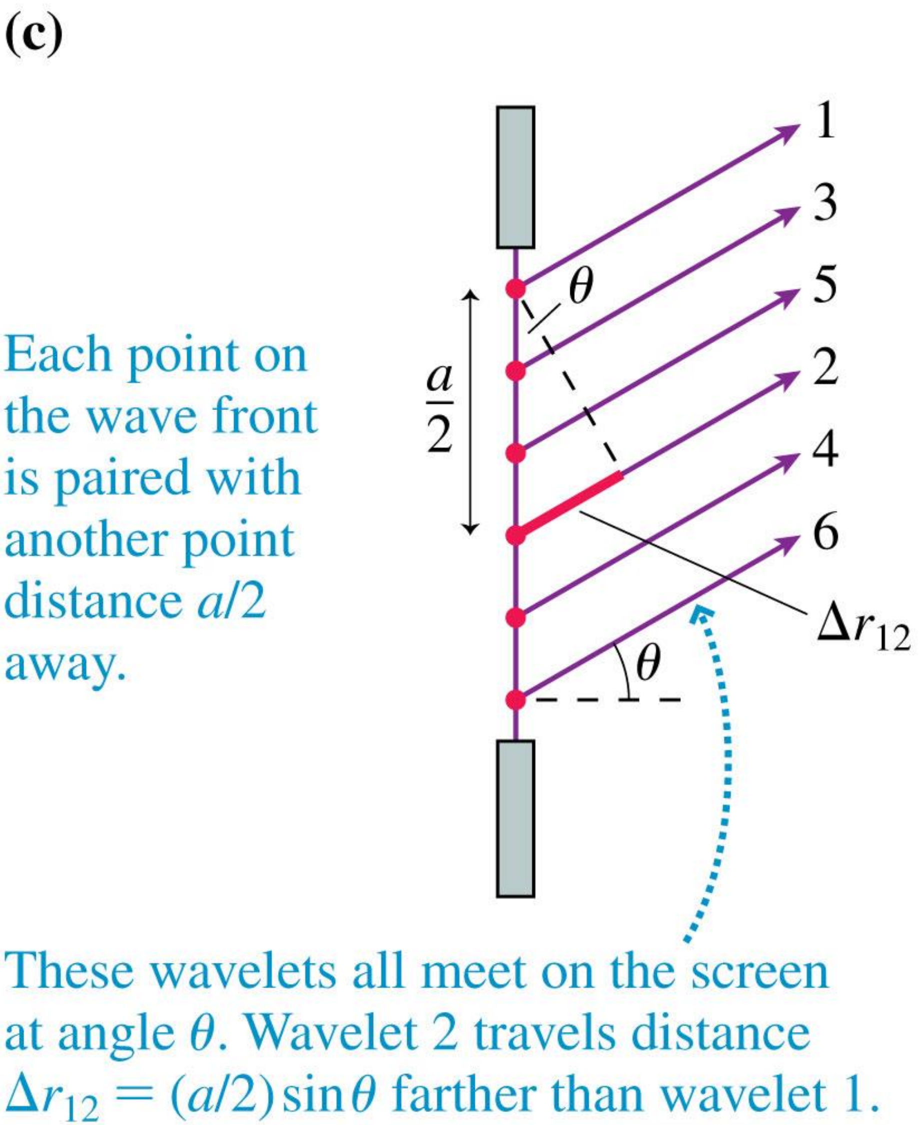
- The paths of several wavelets as they travel straight ahead to a central point on a screen are nearly parallel, and so they are *in phase*.
- Constructive interference will occur, creating the central maximum of the diffraction pattern at $\theta = 0$.



The wavelets going straight forward all travel the same distance to the screen. Thus they arrive in phase and interfere constructively to produce the central maximum.

Analyzing Single-Slit Diffraction

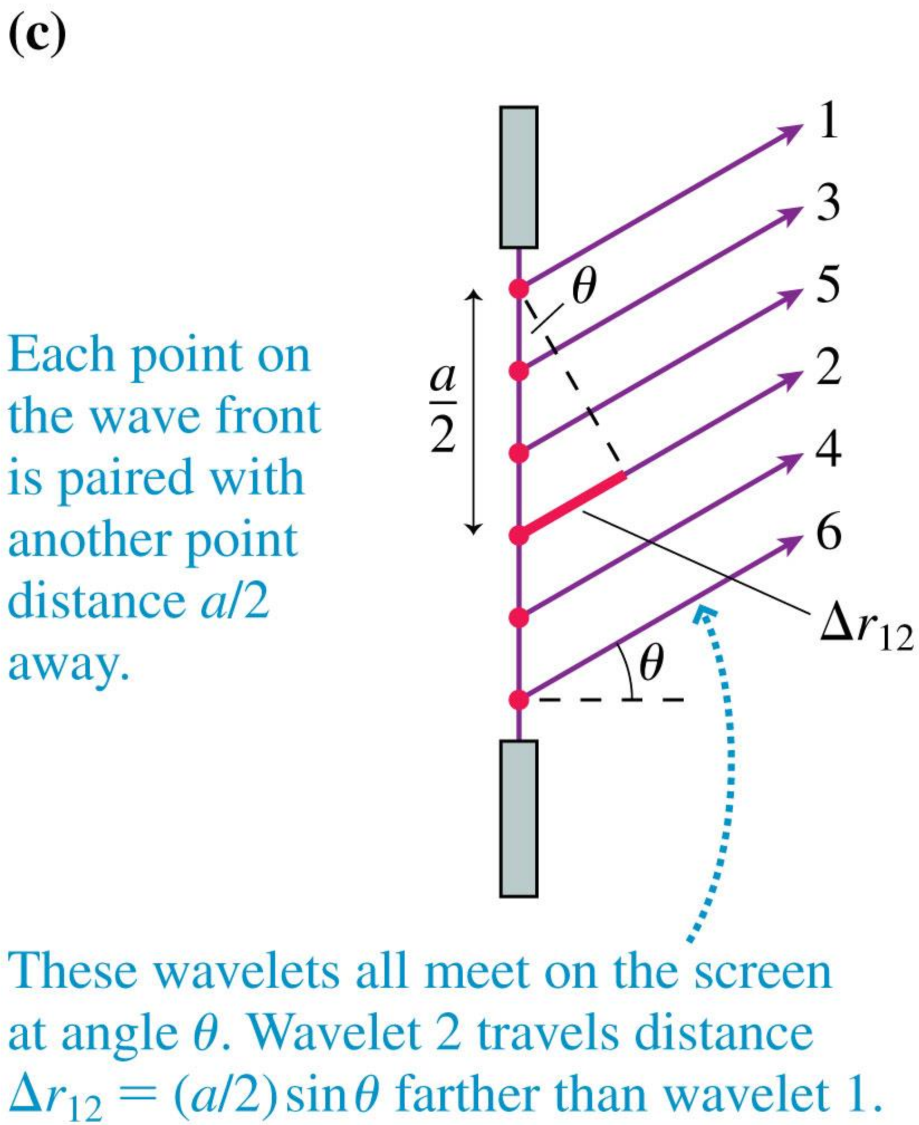
- At points away from the center of the screen, interference occurs.
- Wavelets 1 and 2 start a distance of $a/2$ apart. If Δr_{12} is $\lambda/2$ then the wavelengths are out of phase and interfere destructively.
- If Δr_{12} is $\lambda/2$, then so are Δr_{34} and Δr_{56}, so perfect destructive interference occurs.



Analyzing Single-Slit Diffraction

- **Every point on the wave front can be paired with another point that is a distance *a*/2 away.**
- The condition for destructive interference is

$$\Delta r_{12} = \frac{a}{2}\sin\theta_1 = \frac{\lambda}{2}$$



Analyzing Single-Slit Diffraction

- The general condition for complete destructive interference is

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

- Using the small angle approximation, the condition is written

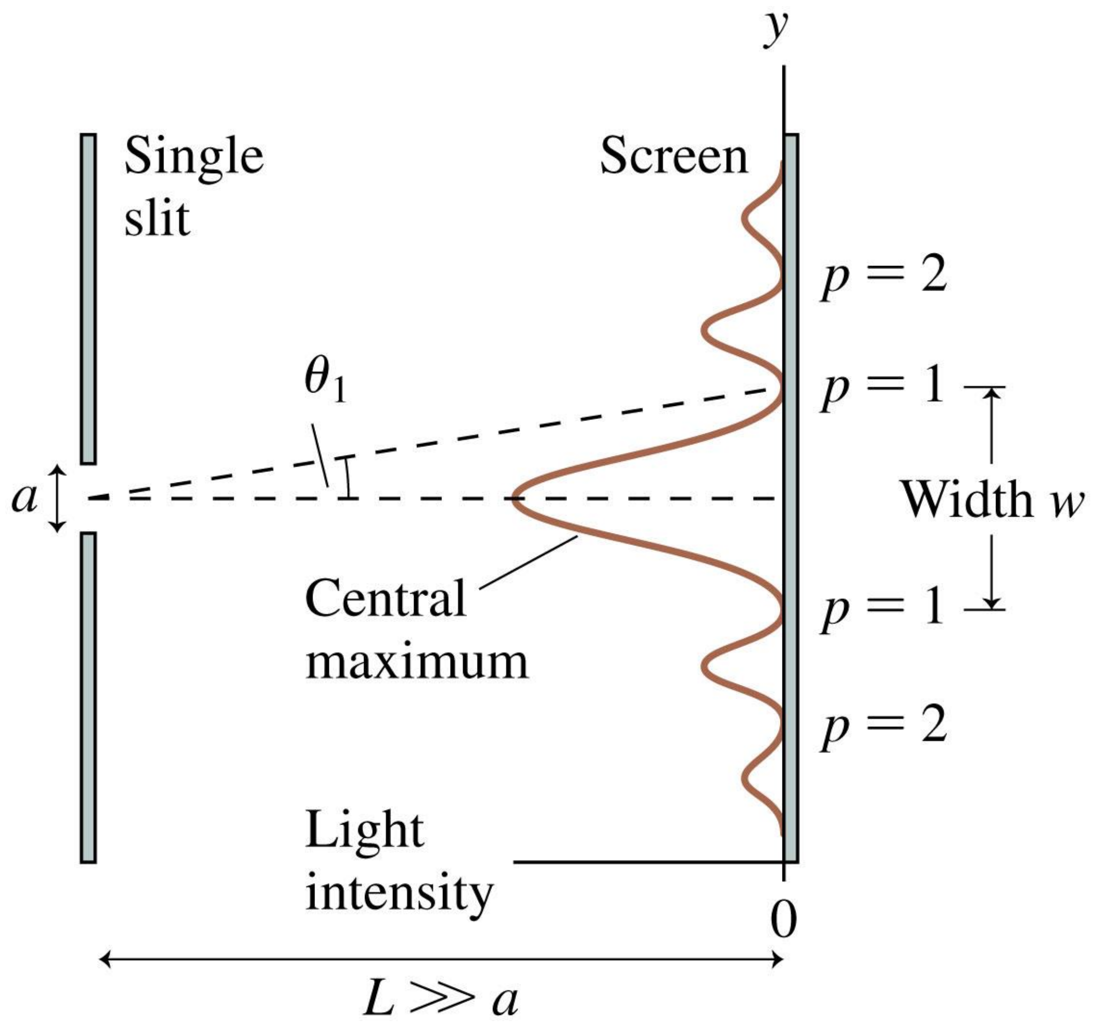
$$\theta_p = p\frac{\lambda}{a} \qquad p = 1, 2, 3, \ldots$$

Angles (in radians) of *dark* fringes in single-slit diffraction with slit width a

- $p = 0$ is specifically excluded because $p = 0$ is the central maximum. The equation for all other p's locates the minima.

Analyzing Single-Slit Diffraction

- The bright central maximum at $\theta = 0$ has the highest intensity.

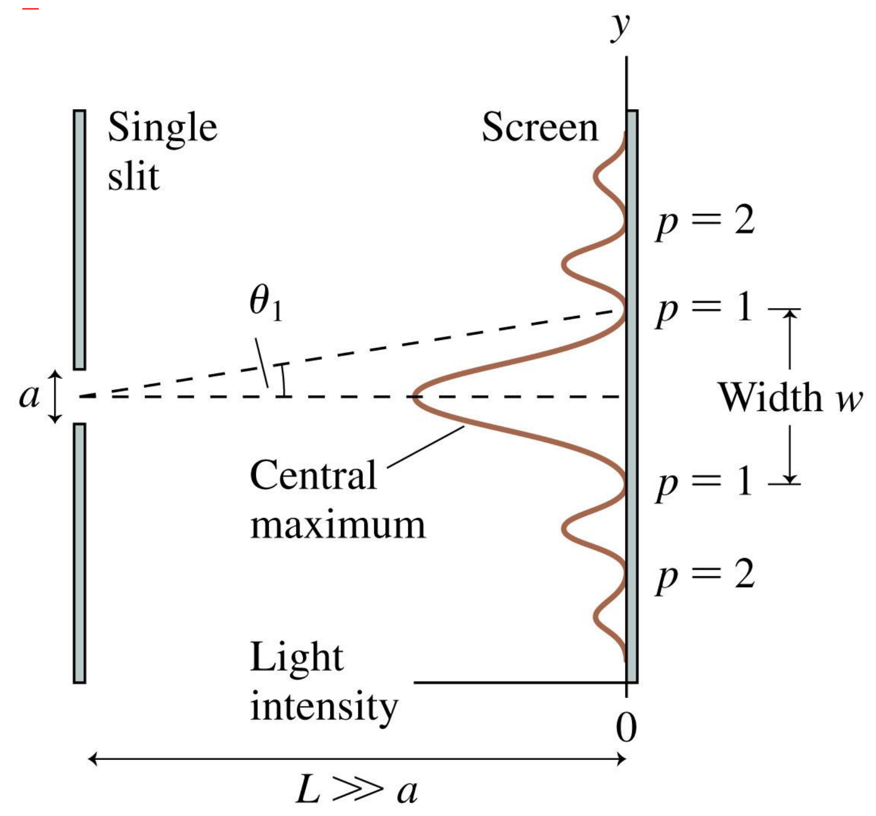


The Width of the Single-Slit Diffraction Pattern

- The dark fringes in the single-slit diffraction pattern are located at

$$y_p = \frac{p\lambda L}{a} \qquad p = 1, 2, 3, \ldots$$

Positions of dark fringes for single-slit diffraction with screen distance L

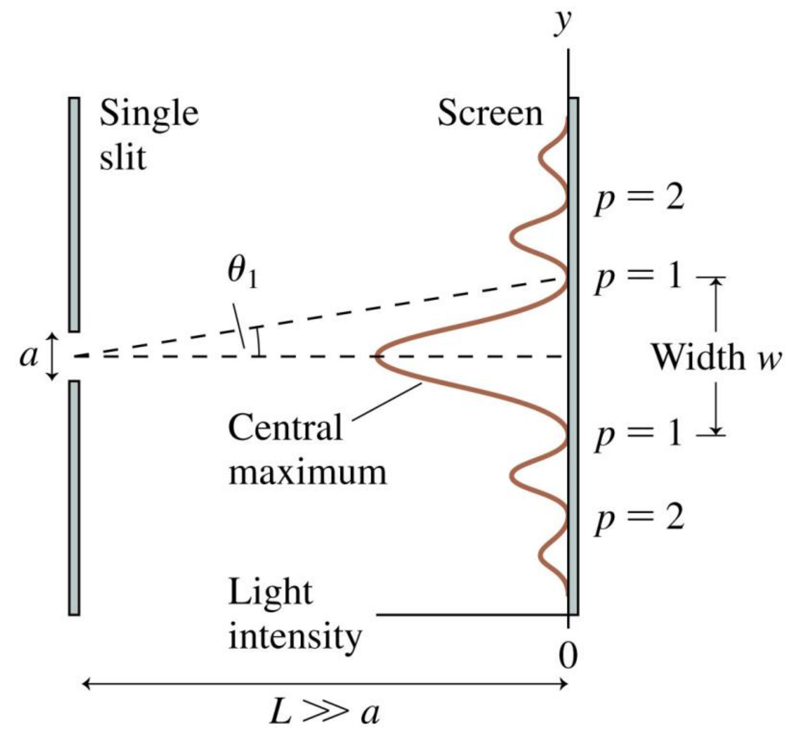


The Width of the Single-Slit Diffraction Pattern

- The width w of the central maximum is defined as the distance between the two $p = 1$ minima, which is simply $w = 2y_1$.

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

Width of the central maximum for single-slit diffraction



- Counterintuitively, **the smaller the opening a wave squeezes through, the *more* it spreads out on the other side.**

QuickCheck 17.9

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 17.9

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.

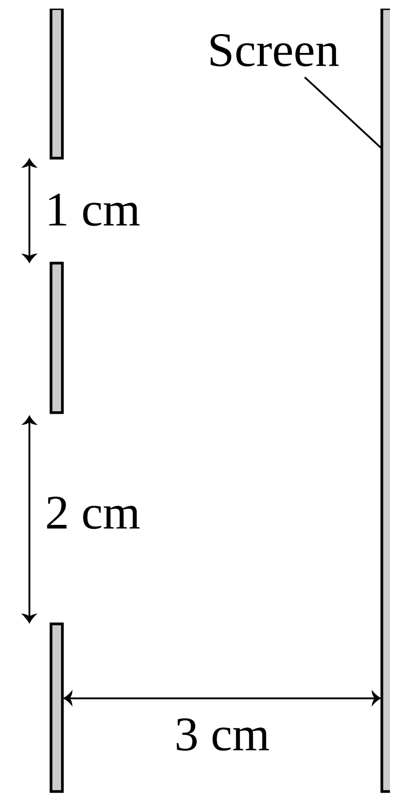
Minima between the bright fringes are at $y_p = \frac{p\lambda L}{a}$.

QuickCheck 17.10

Each of the slits is separately illuminated by a broad laser beam. Which produces a broader brightly illuminated region on the screen at the right?

A. The 1-cm-wide slit

B. The 2-cm-wide slit



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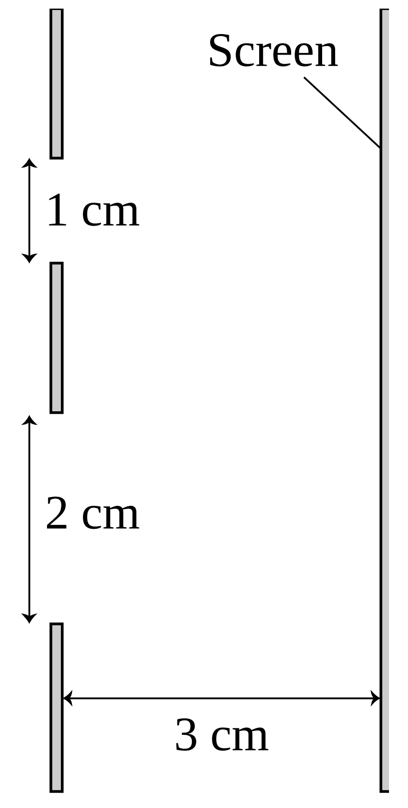
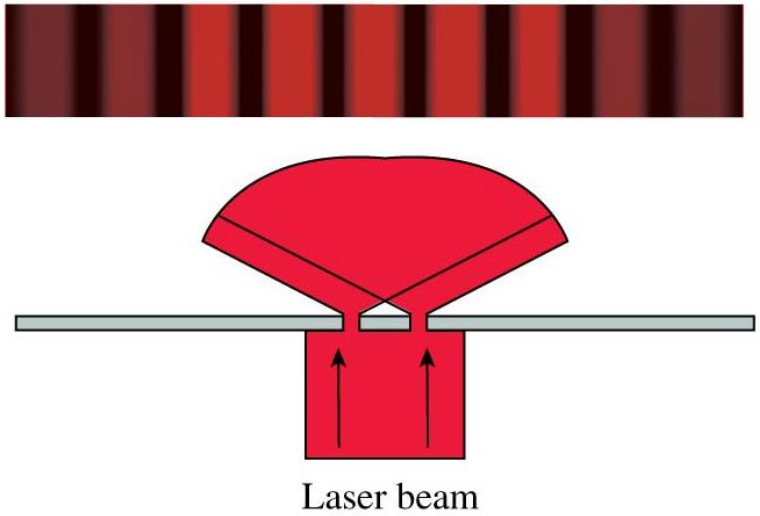


QuickCheck 17.11

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



A.

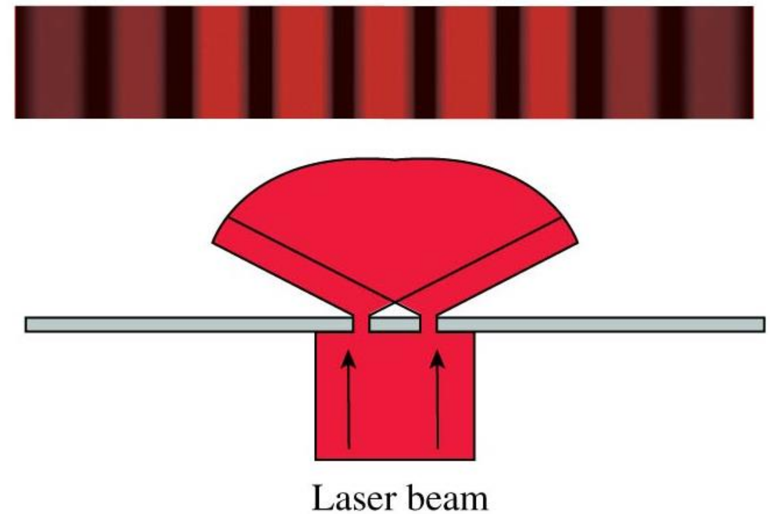
B.

C.

D.

QuickCheck 17.11

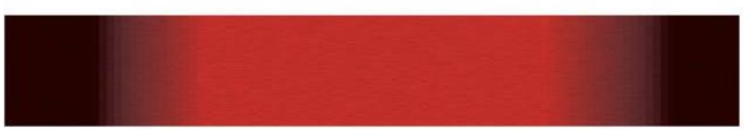
A laboratory experiment produces a double-slit interference pattern on a screen. If the left slit is blocked, the screen will look like



A. 

B. 

C. 

D. 

QuickCheck 17.12

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 17.12

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

Example 17.8 Finding the width of a slit

Light from a helium-neon laser (λ = 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 middle of the central maximum. How wide is the slit?

PREPARE The first minimum in a diffraction pattern corresponds to $p = 1$. The position of this minimum is given as $y_1 = 1.2$ cm. We can then use Equation 17.19 to find the slit width a.

Example 17.8 Finding the width of a slit (cont.)

SOLVE Equation 17.19 gives

$$a = \frac{p\lambda L}{y_p} = \frac{(1)(633 \times 10^{-9}\ \text{m})(2.0\ \text{m})}{0.012\ \text{m}}$$

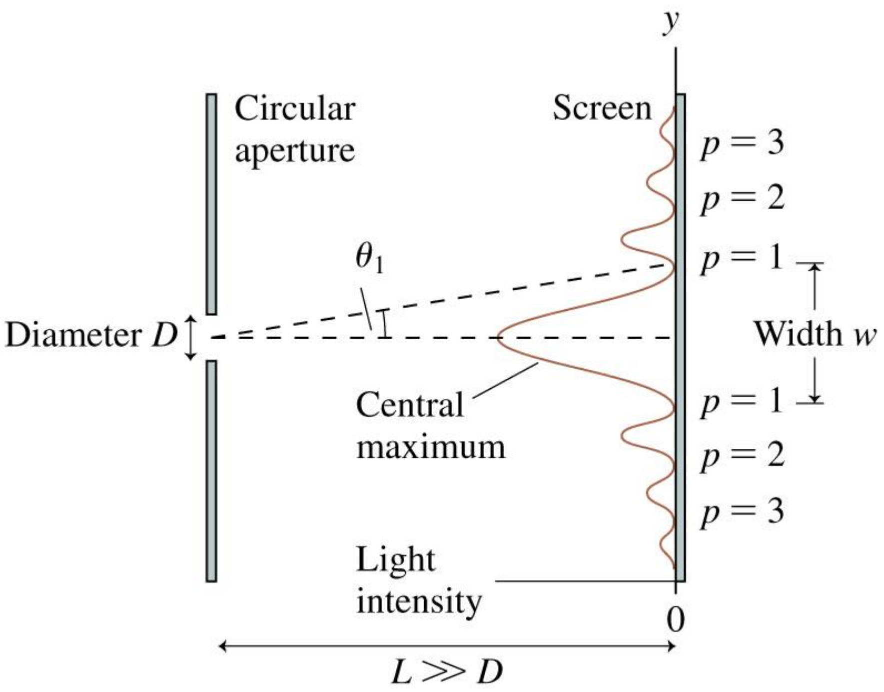
$$= 1.1 \times 10^{-4}\ \text{m} = 0.11\ \text{mm}$$

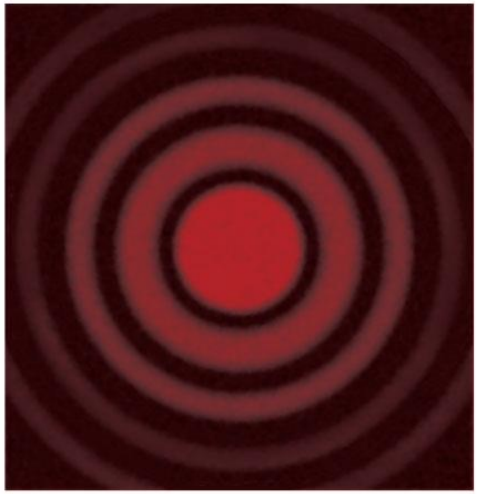
ASSESS This value is typical of the slit widths used to observe single-slit diffraction.

Section 17.6 Circular-Aperture Diffraction

Circular-Aperture Diffraction

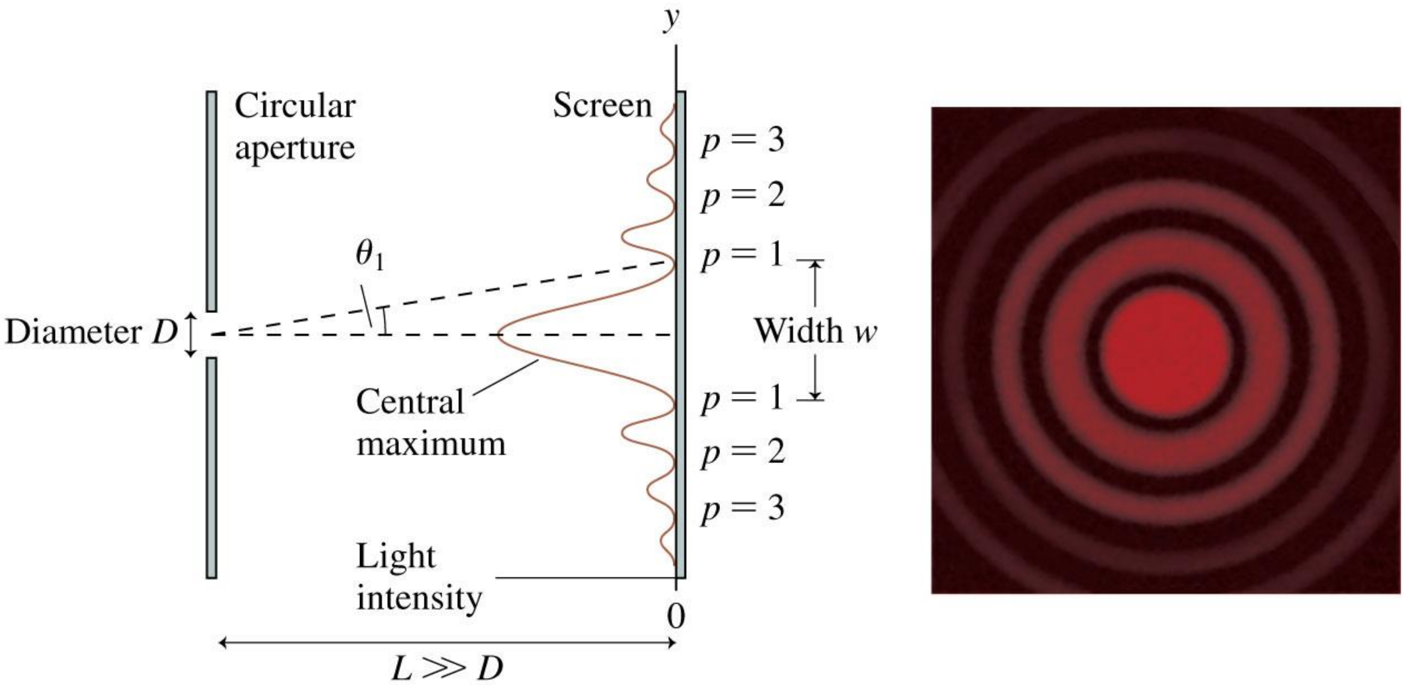
- Diffraction occurs if a wave passes through an opening of any shape, but an important example is a circular aperture.
- Light waves passing through a circular aperture spread out to generate a *circular* diffraction pattern.





Circular-Aperture Diffraction

- Most of the intensity is contained in the circular central maximum, which is surrounded by a series of secondary bright fringes.



Circular-Aperture Diffraction

- Angle θ_1 locates the first minimum in the intensity for a circular aperture of diameter D.

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

- The width of the central maximum on a screen a distance L from the aperture is

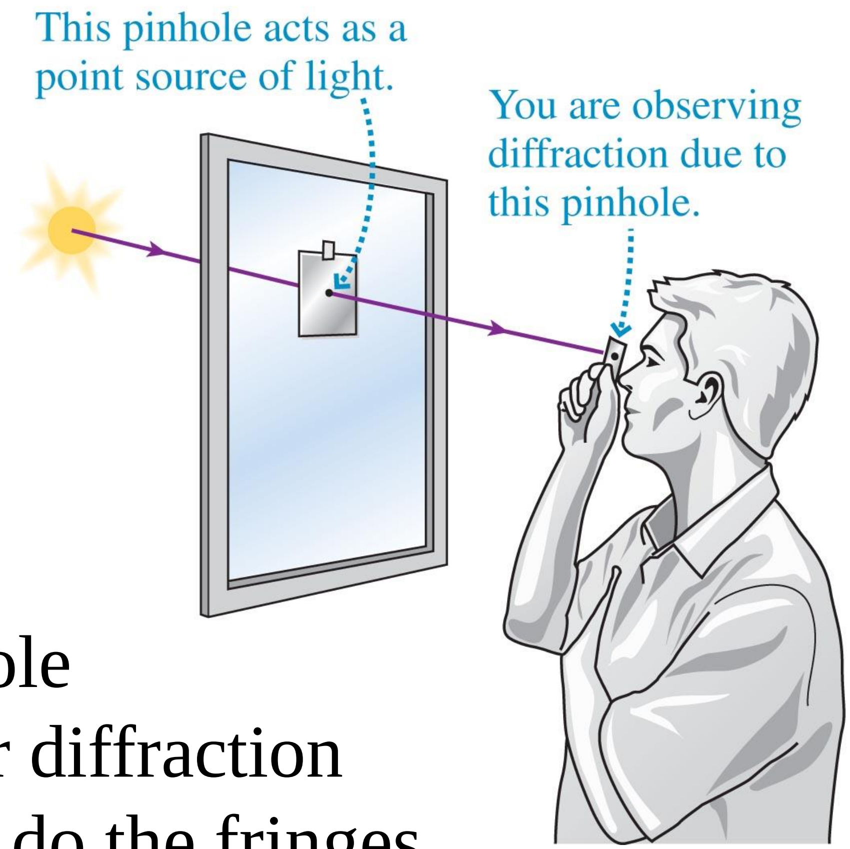
$$w = 2y_1 = 2L\tan\theta_1 \approx \frac{2.44\lambda L}{D}$$

Width of central maximum for diffraction from a circular aperture of diameter D

Circular-Aperture Diffraction

- The diameter of the diffraction pattern increases with L (the wave spreads out as it travels) but decreases with increasing D.

Try It Yourself: Observing Diffraction



To observe diffraction from a circular aperture, use a pin to prick a *very* small hole in each of two pieces of aluminum foil. Tape one piece up to a window that faces the sun. Then, holding the other hole close to your eye, observe the sun through the pinhole on the window. You will see clear diffraction fringes around that pinhole. How do the fringes vary if you change the size of the pinhole near your eye? **(CAUTION: Don't look directly at the sun except through the two pinholes!)**

Example 17.9 Finding the right viewing distance

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 17.22 gives us the appropriate screen distance:

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

Summary: General Principles

The Wave Model

The wave model considers light to be a wave propagating through space. Interference and diffraction are important. The wave model is appropriate when light interacts with objects whose size is comparable to the wavelength of light, or roughly less than about 0.1 mm.

Text: p. 558

Summary: 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.

Text: p. 558

Summary: Important Concepts

The **index of refraction** of a material determines the speed of light in that material: $v = c/n$. The index of refraction of a material is always greater than 1, so that v is always less than c.

The wavelength λ in a material with index of refraction n is *shorter* than the wavelength λ_{vac} in a vacuum: $\lambda = \lambda_{vac}/n$.

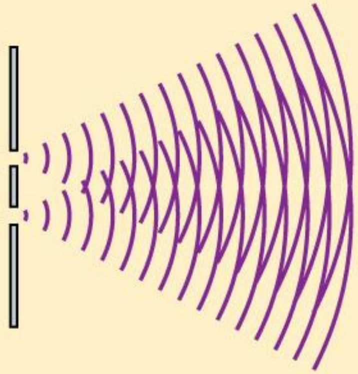
The *frequency* of light does not change as it moves from one material to another.

Text: p. 558

Summary: Important Concepts

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.



Text: p. 558

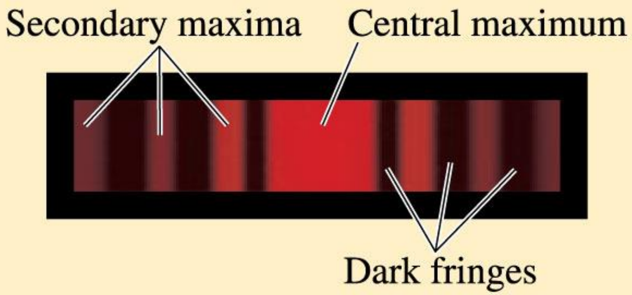
Summary: Applications

Diffraction from a single slit

A single slit of width a has a bright **central maximum** of width

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

that 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,

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

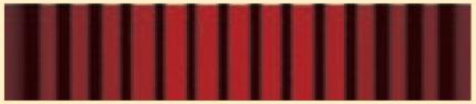
Text: p. 558

Summary: Applications

Interference from multiple slits

Waves overlap as they spread out behind slits. Bright fringes are seen on the viewing screen at positions where the path-length difference Δr between successive slits is equal to $m\lambda$, where m is an integer.

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 $\Delta y = \dfrac{\lambda L}{d}$

Diffraction grating with slit spacing d

Very bright and narrow fringes are located at angles and positions

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

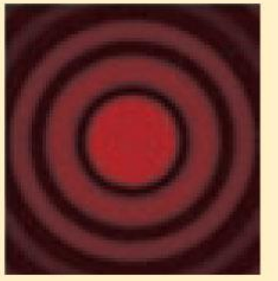
Text: p. 558

Summary: 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 greater spreading of the wave behind the opening.

Text: p. 558

Summary: Applications

Thin-film interference

Interference occurs between the waves reflected from the two surfaces of a thin film with index of refraction n. A wave that reflects from a surface at which the index of refraction increases has a phase change.

Interference	0 or 2 phase changes	1 phase change
Constructive	$2t = m\frac{\lambda}{n}$	$2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$
Destructive	$2t = \left(m + \frac{1}{2}\right)\frac{\lambda}{n}$	$2t = m\frac{\lambda}{n}$

Text: p. 558

Summary

GENERAL PRINCIPLES

The Wave Model

The wave model considers light to be a wave propagating through space. Interference and diffraction are important. The wave model is appropriate when light interacts with objects whose size is comparable to the wavelength of light, or roughly less than about 0.1 mm.

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.

Text: p. 558

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IMPORTANT CONCEPTS

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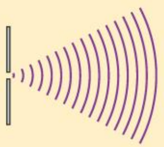
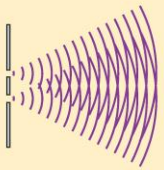


Constructive and destructive **interference** are due to the overlap of two or more waves as they spread behind openings.



Text: p. 558

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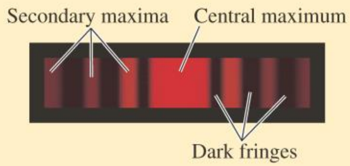

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Circular aperture of diameter D

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Text: p. 558