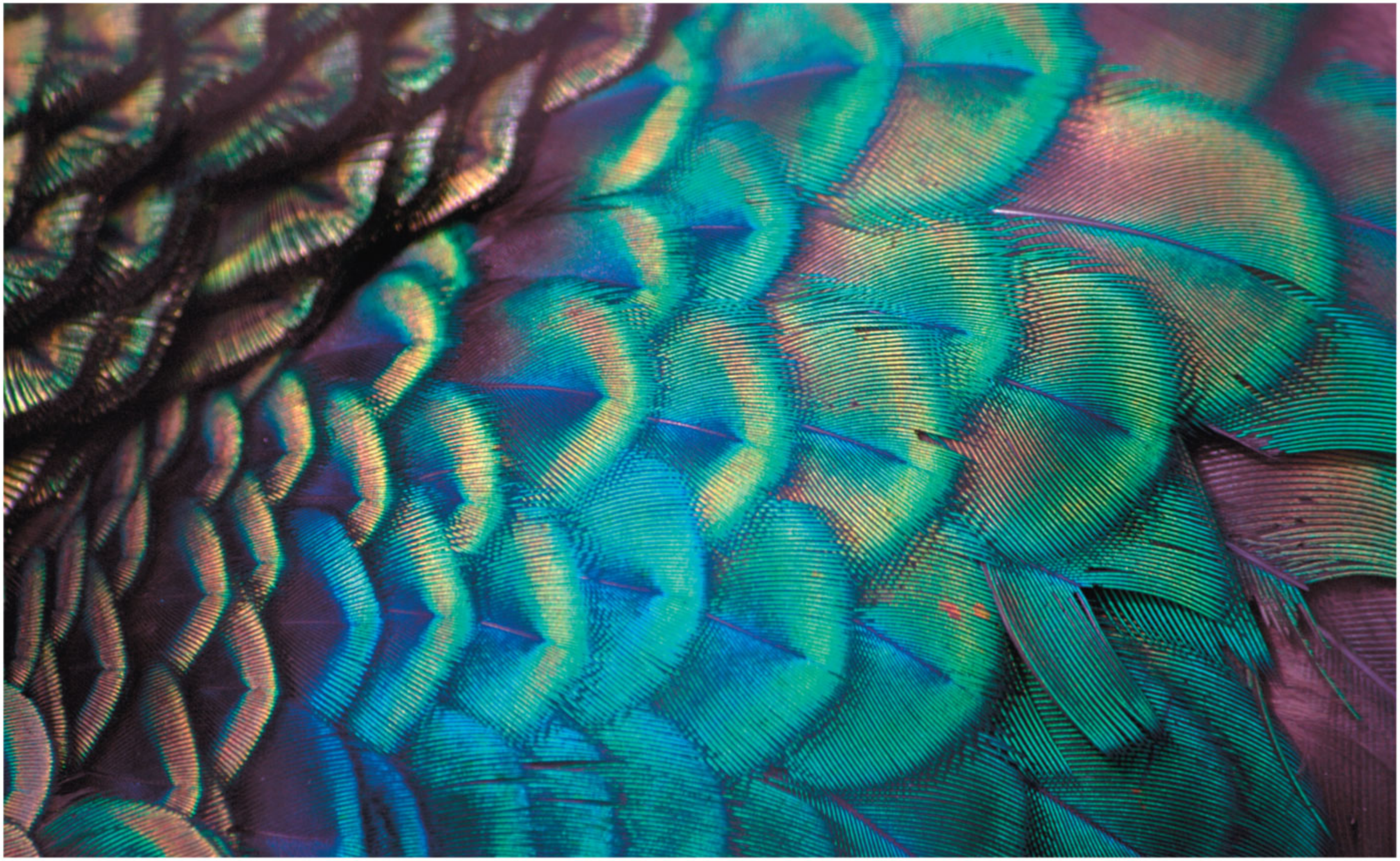
Interference and Diffraction

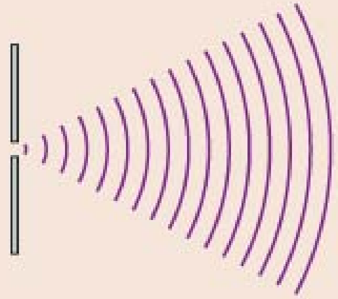
A Diffraction Grating



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

Diffraction

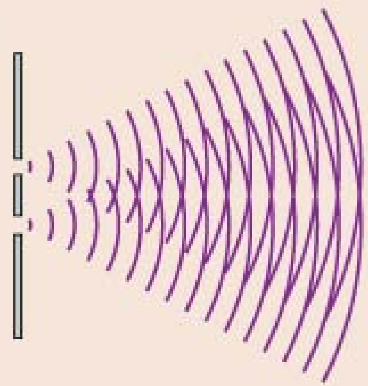
Diffraction is the ability of waves to spread out after going through small holes or around corners. The diffraction of light indicates that light is a wave.

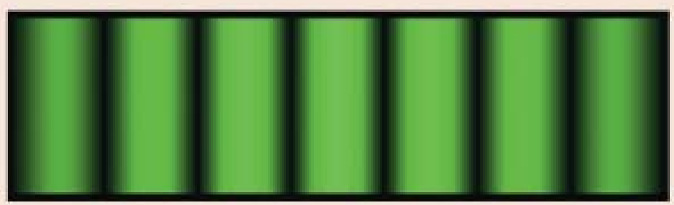


The "ripples" around the edges of this razor blade—back lit with a blue laser beam—are due to the diffraction of light.and interference

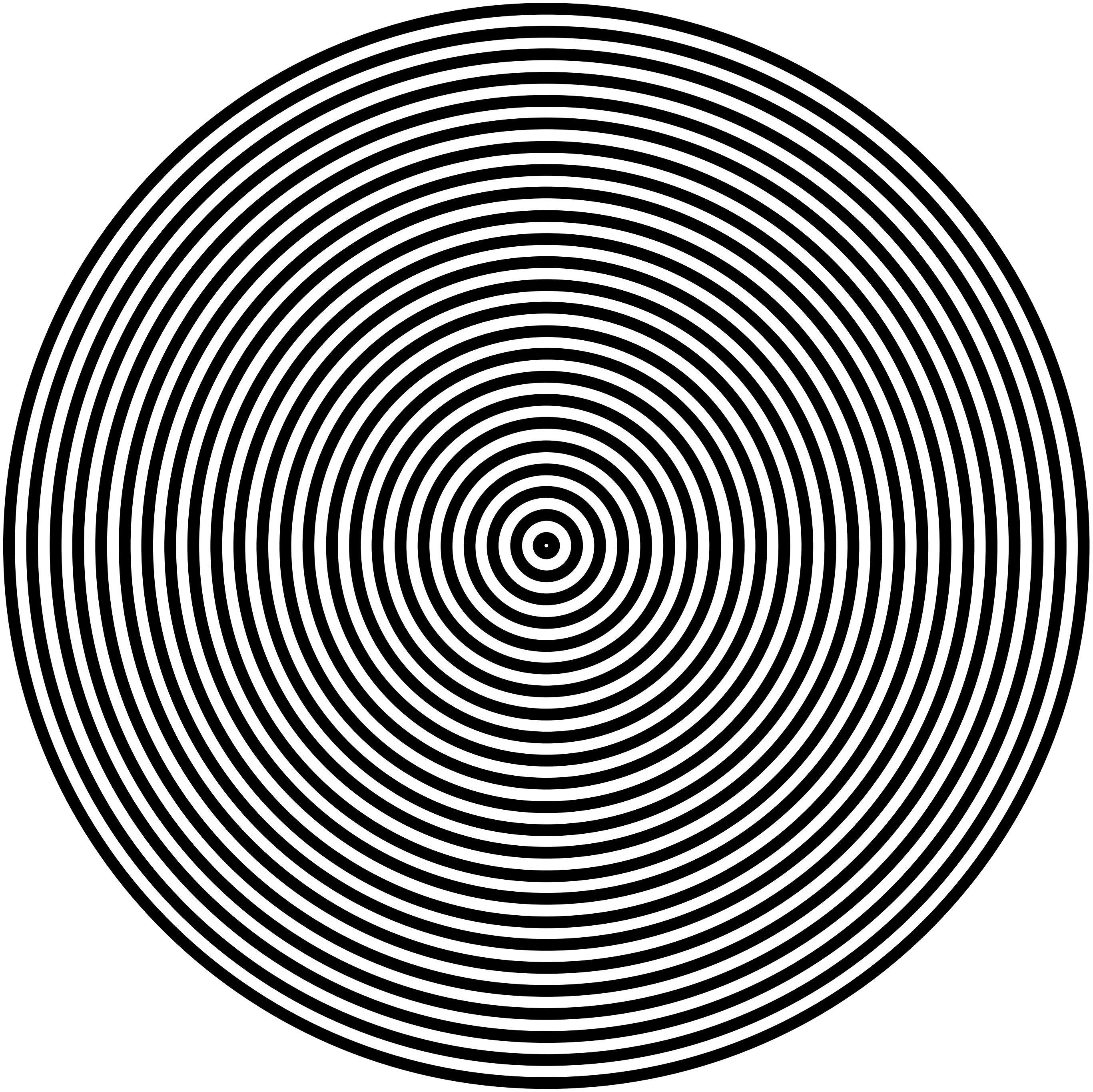
Double-Slit Interference

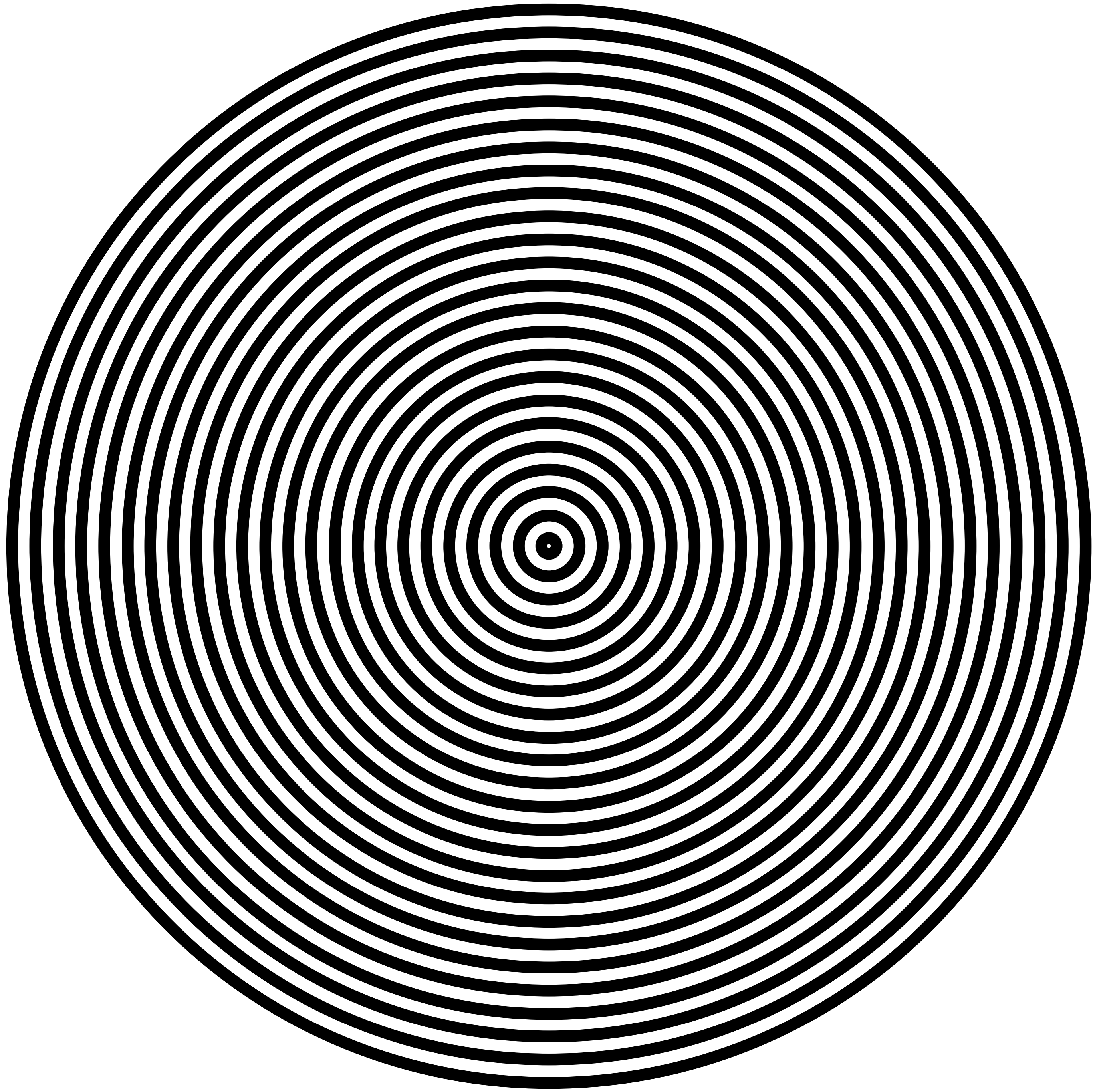
You'll learn that an interference pattern is formed when light shines on an opaque screen with two narrow, closely spaced slits. This also shows that light is a wave.

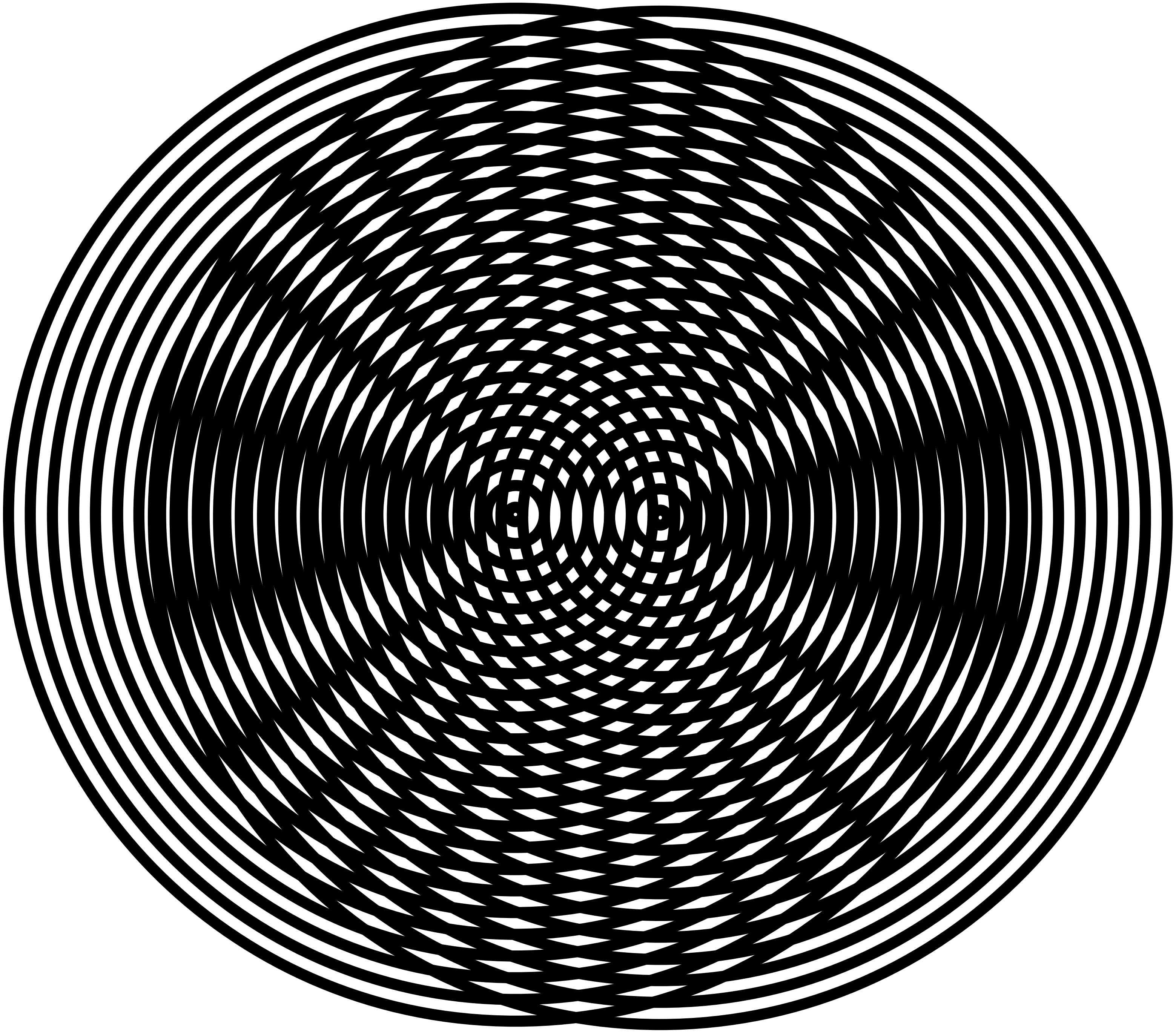


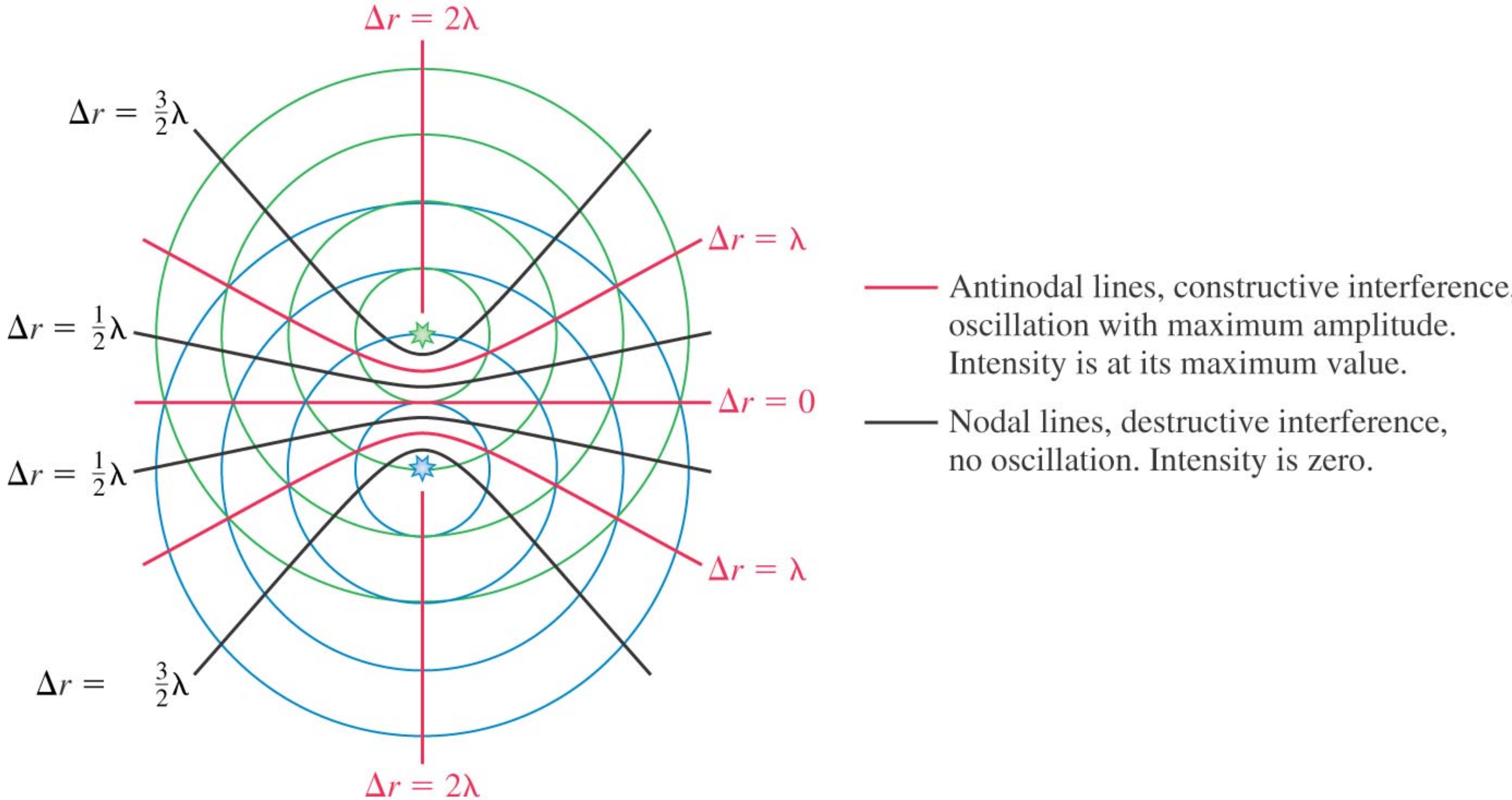


Interference fringes from green light passing through two closely spaced slits



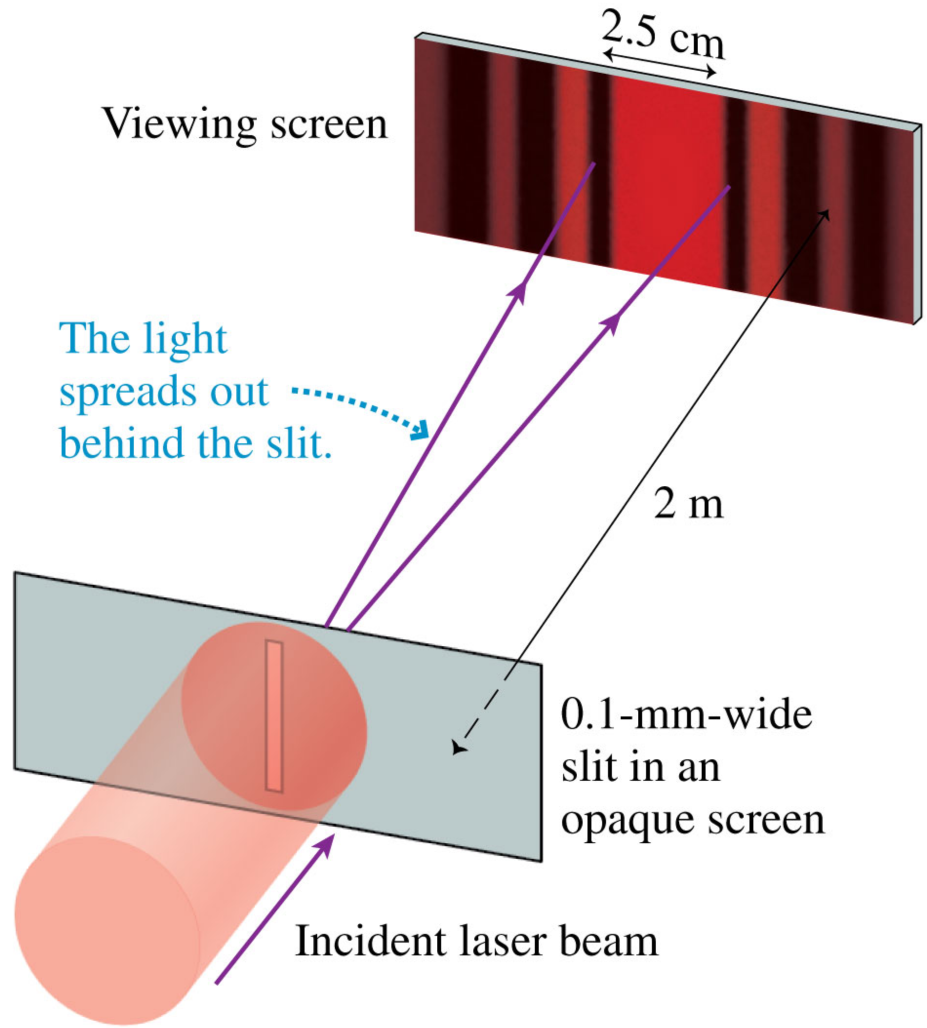


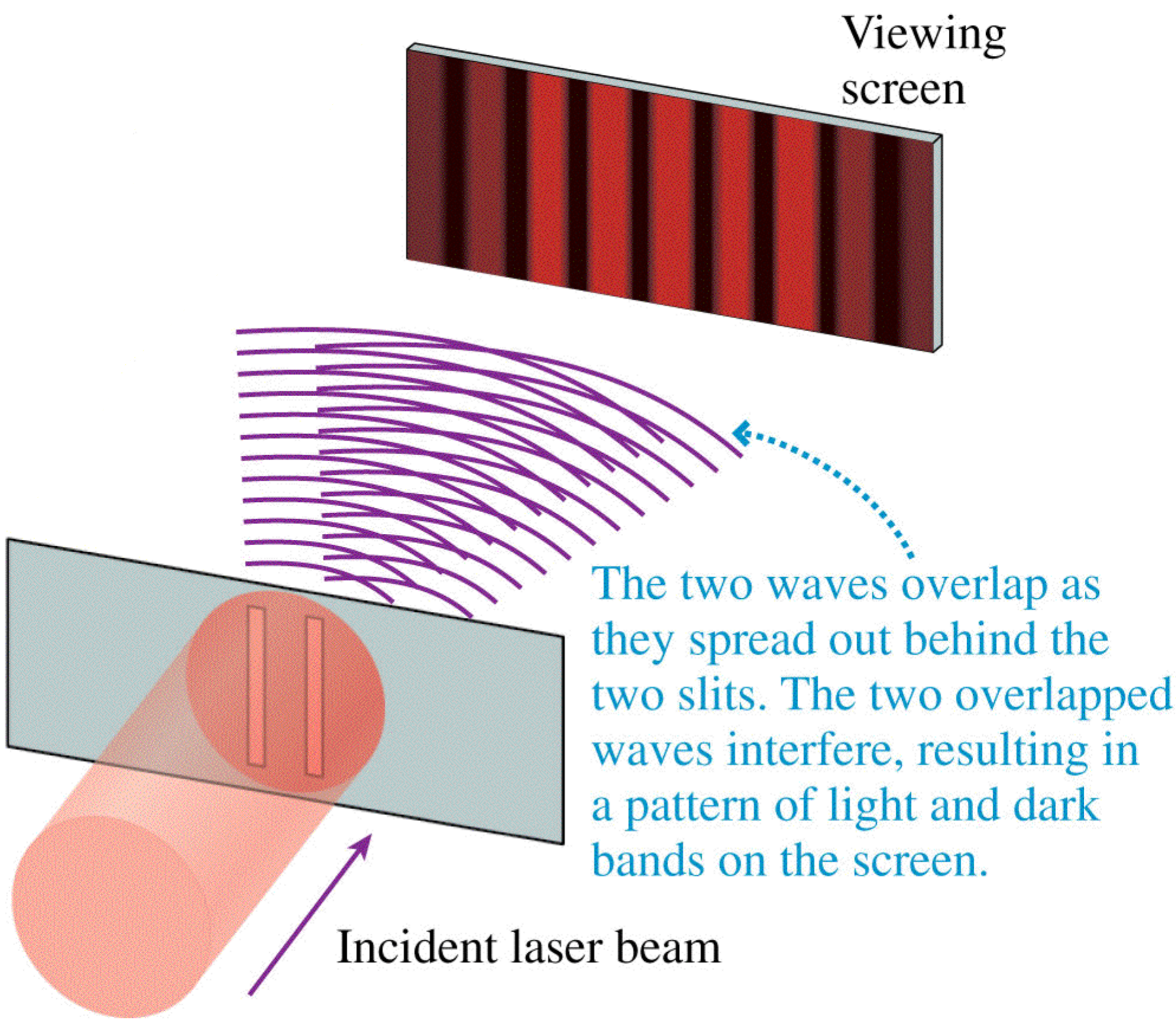


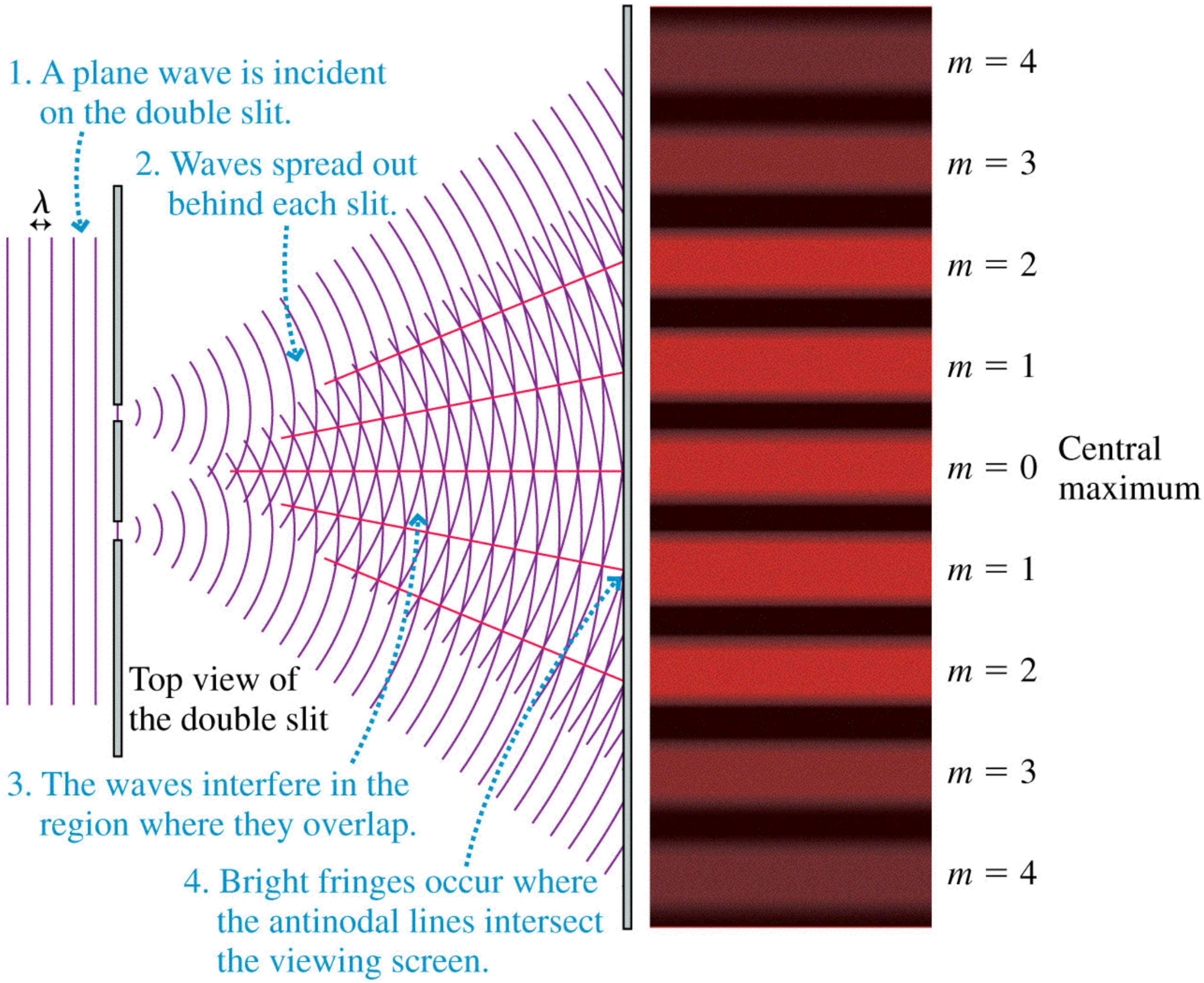


$\Delta r = 2\lambda$
$\Delta r = \frac{3}{2}\lambda$
$\Delta r = \lambda$
$\Delta r = \frac{1}{2}\lambda$
$\Delta r = 0$
$\Delta r = \frac{1}{2}\lambda$
$\Delta r = \lambda$
$\Delta r = \frac{3}{2}\lambda$
$\Delta r = 2\lambda$
Antinodal lines, constructive interference, oscillation with maximum amplitude. Intensity is at its maximum value.
Nodal lines, destructive interference, no oscillation. Intensity is zero.

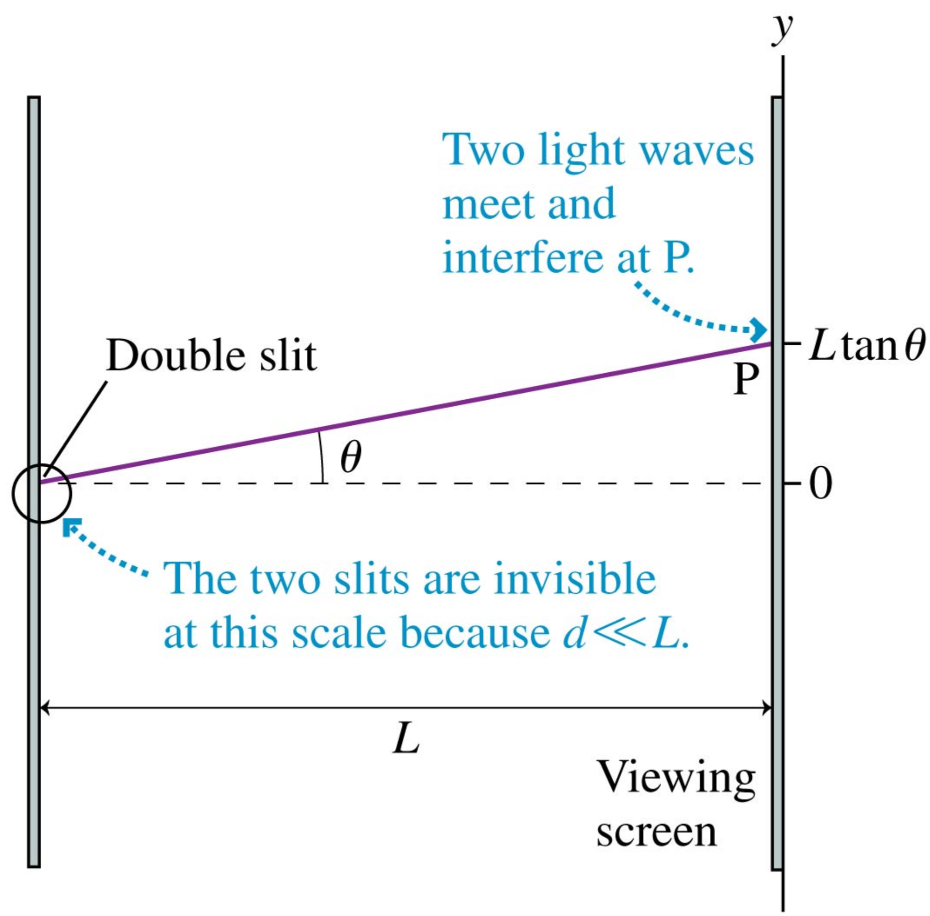
- When red light passes through an opening that is only $0.1\ \text{mm}$ wide, it does spread out.
- Diffraction of light is observable *if* the hole is sufficiently small.




Viewing
screen
The two waves overlap as
they spread out behind the
two slits. The two overlapped
waves interfere, resulting in
a pattern of light and dark
bands on the screen.
Incident laser beam


1. A plane wave is incident on the double slit.
λ
2. Waves spread out behind each slit.
Top view of the double slit
3. The waves interfere in the region where they overlap.
4. Bright fringes occur where the antinodal lines intersect the viewing screen.
m = 4
m = 3
m = 2
m = 1
m = 0
Central maximum
m = 1
m = 2
m = 3
m = 4

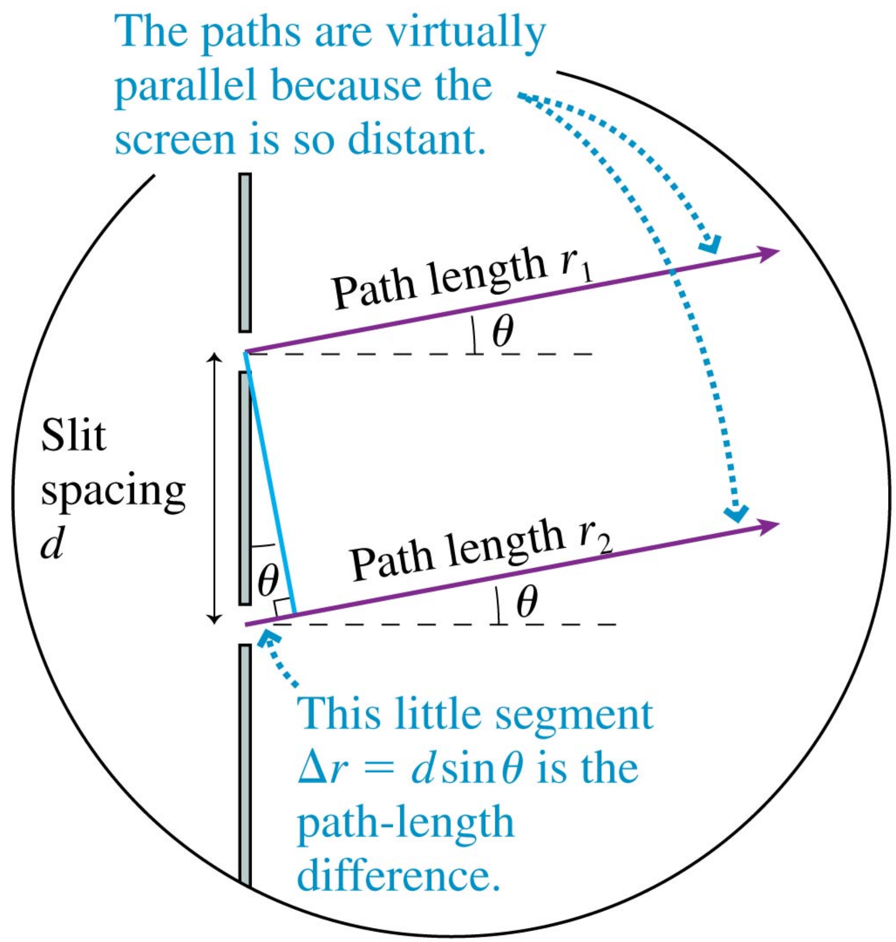
- The figure shows the "big picture" of the double-slit experiment.
- The next slide *zooms in* on the area inside the circle.



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



- 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:

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

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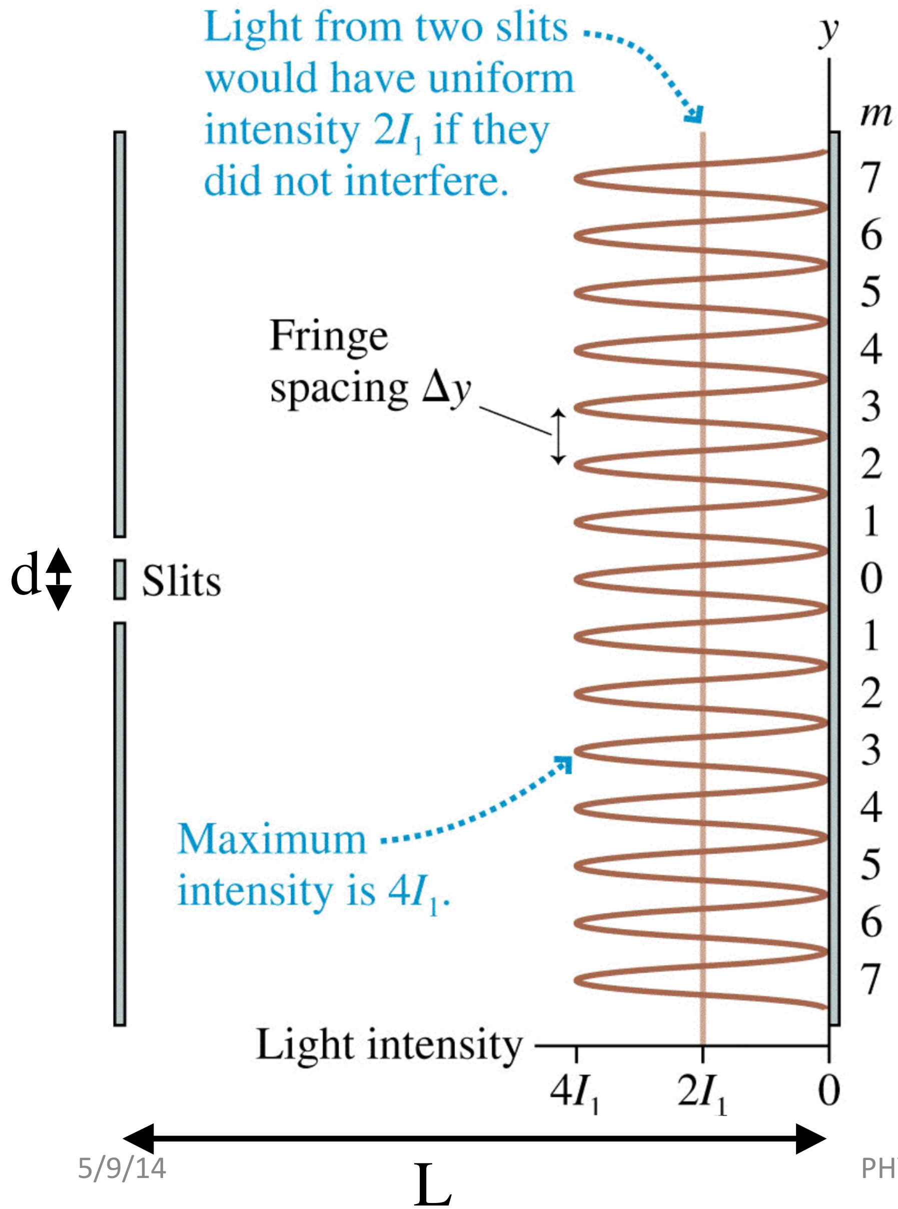
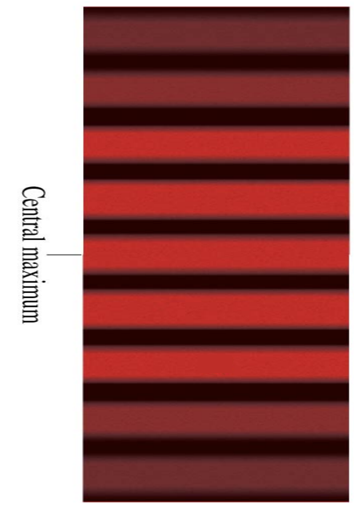
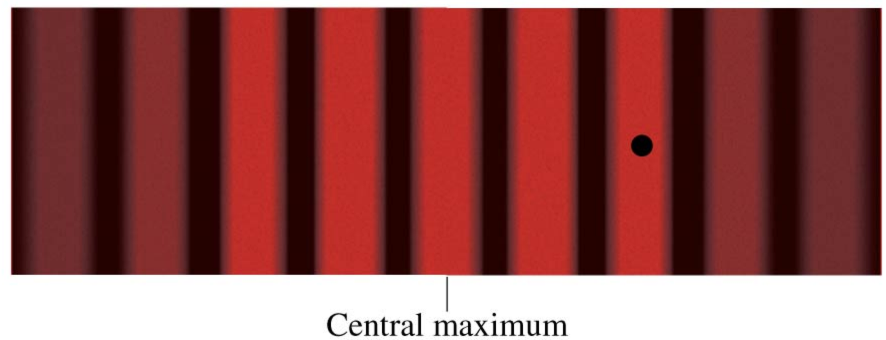




Positions of dark fringes

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

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. $1.0\ \lambda$.

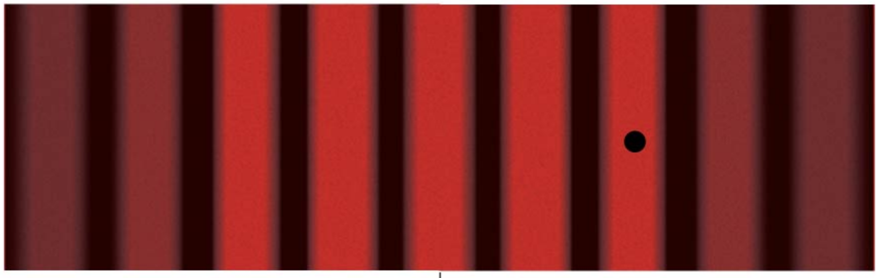
B. $1.5\ \lambda$.

C. $2.0\ \lambda$.

D. $2.5\ \lambda$.

E. $3.0\ \lambda$.

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.

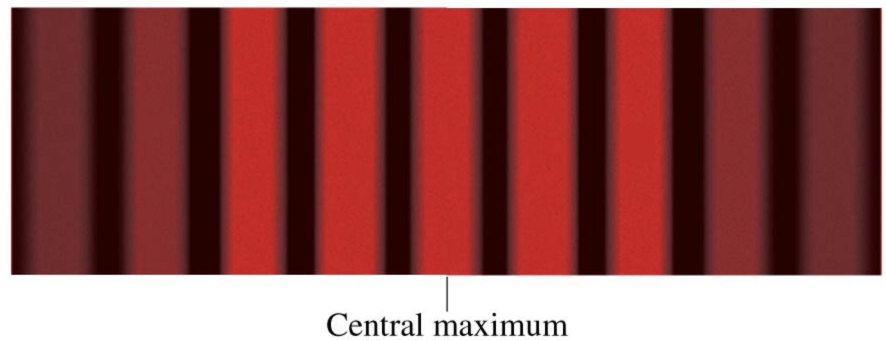
B. 1.5 λ.

✔ **C. 2.0 λ.**

D. 2.5 λ.

E. 3.0 λ.

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.

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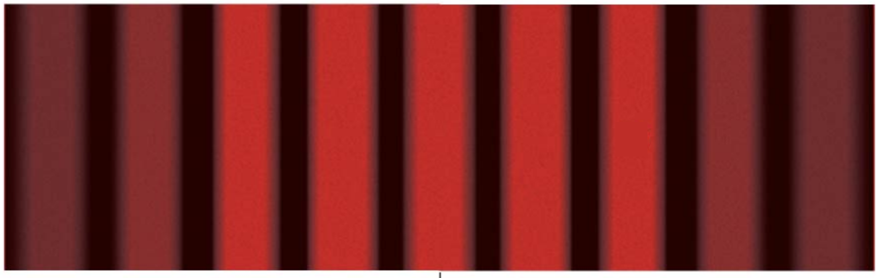


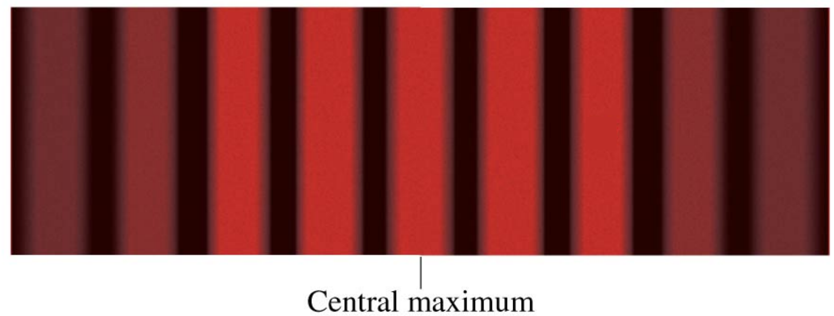
A. Closer together.

B. In the same positions.

✔ **C. Farther apart.**

D. Fuzzy and out of focus.

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.

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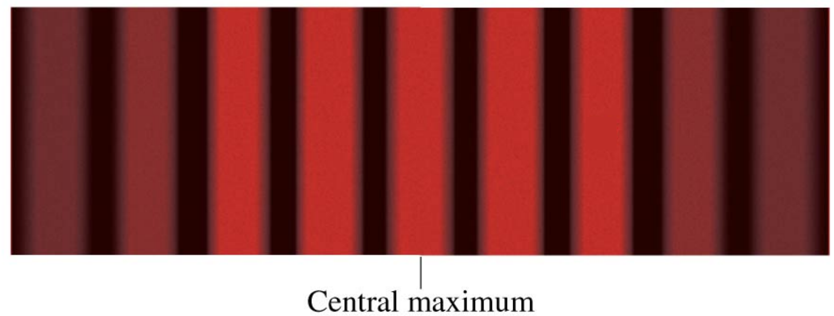


✔ **A. Closer together.**

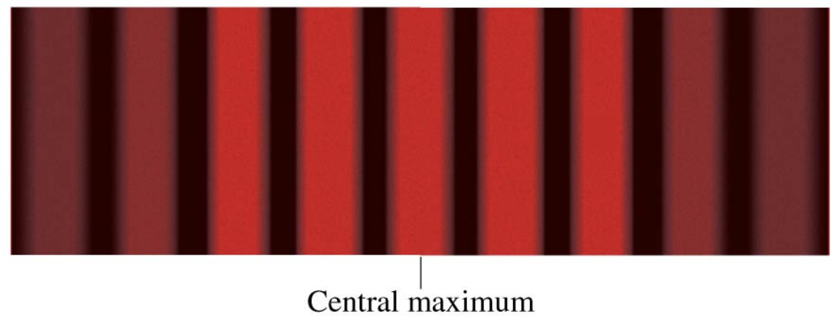
B. In the same positions.

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.

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



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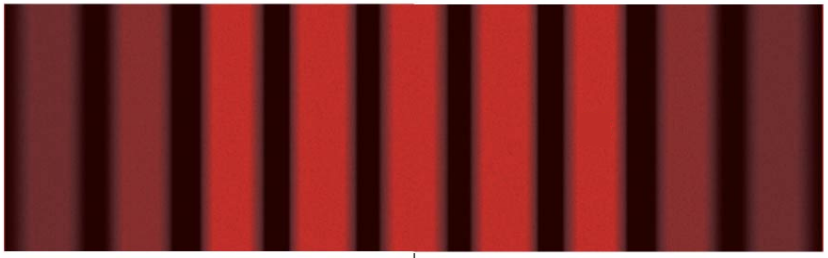
A laboratory experiment produces a double-slit interference pattern on a screen. If the slits are moved closer together, the bright fringes will be



Central maximum

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.

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

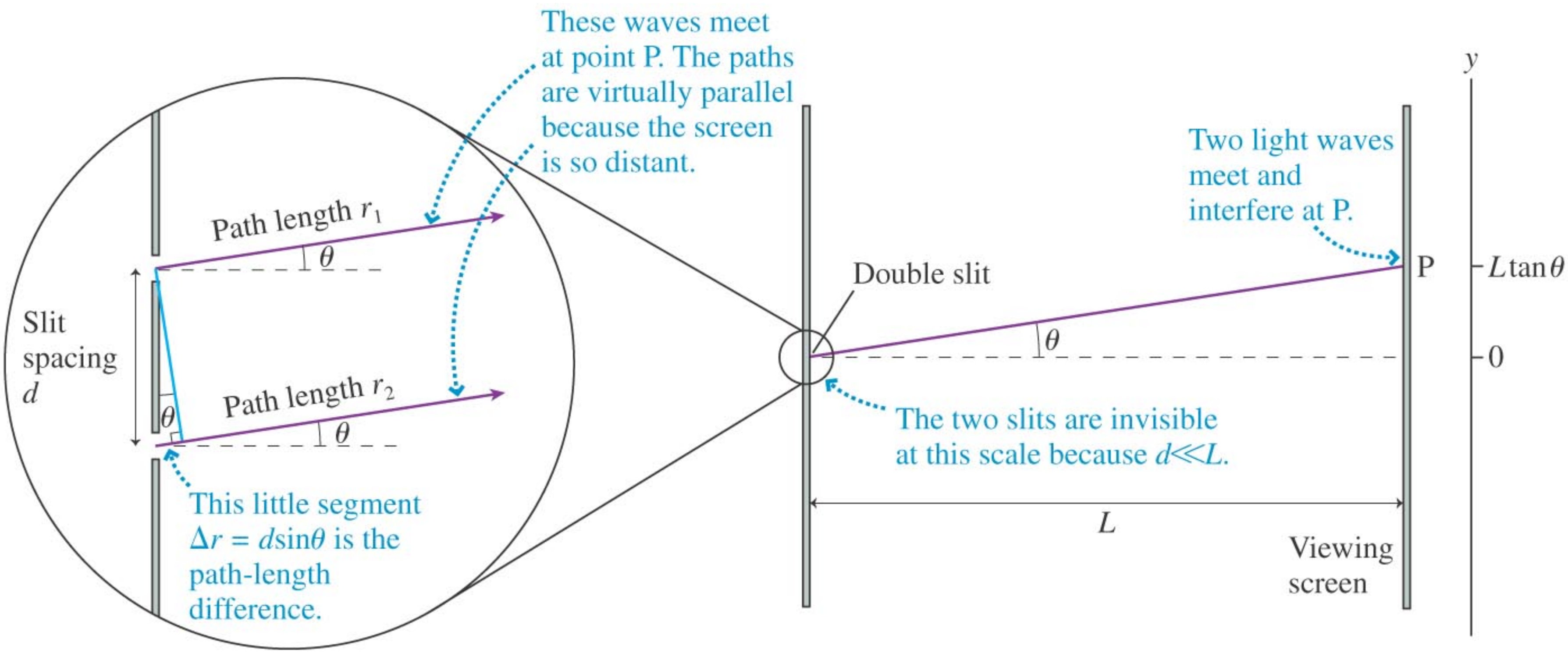
Example 22.1 Double-Slit Interference of a Laser Beam

EXAMPLE 22.1 Double-slit interference of a laser beam

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

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

Whiteboard, TA & LA



Sources will interfere constructively (bright) when

$$\Delta r = m\lambda \qquad d\sin\theta = m\lambda$$

$$\sin\theta_m \approx \theta_m = m\lambda / d$$

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

Phases same because source comes from a single incident plane wave

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

Dark fringes $\quad \sin\theta_m \approx \theta_m = \left(m + \frac{1}{2}\right)\lambda / d$

Example 22.1 Double-Slit Interference of a Laser Beam

EXAMPLE 22.1 **Double-slit interference of a laser beam**

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

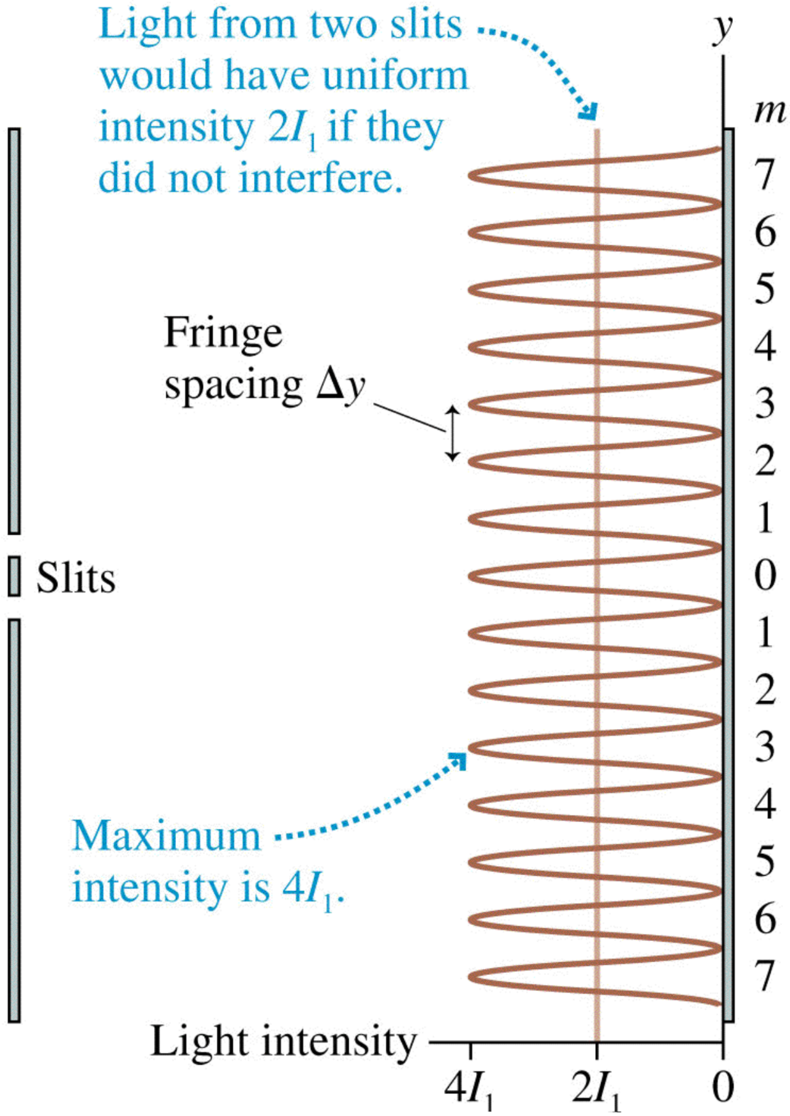
$$y_m = \frac{m\lambda L}{d} = \frac{2(633 \times 10^{-9}\ \text{m})(2.0\ \text{m})}{4.0 \times 10^{-4}\ \text{m}} = 6.3\ \text{mm}$$

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

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

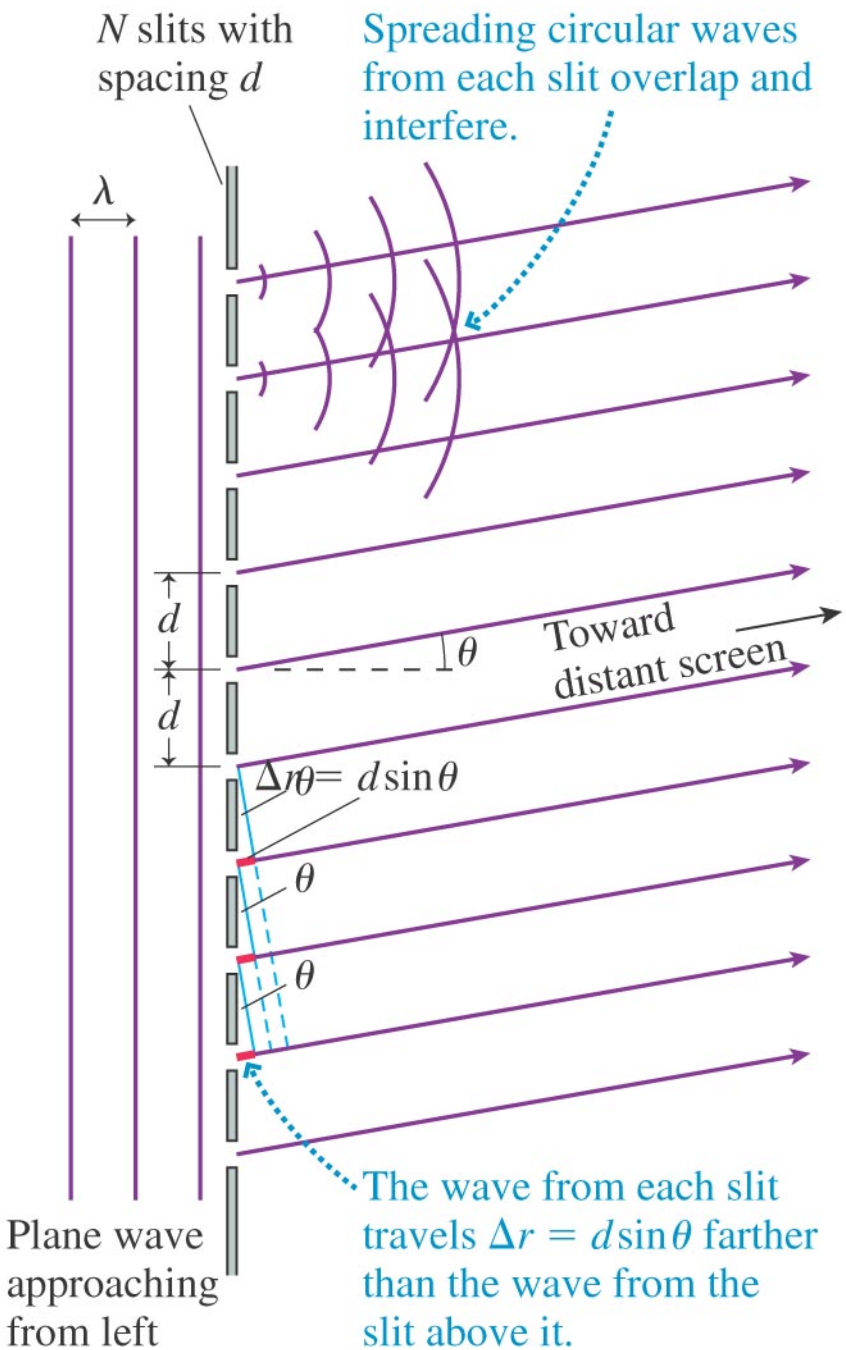
Thus the distance between the two $m = 2$ dark fringes is 15.8 mm.

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



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

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



If two slits are good, more slits are better.

Diffraction Grating
N slits, sharpens bright fringes

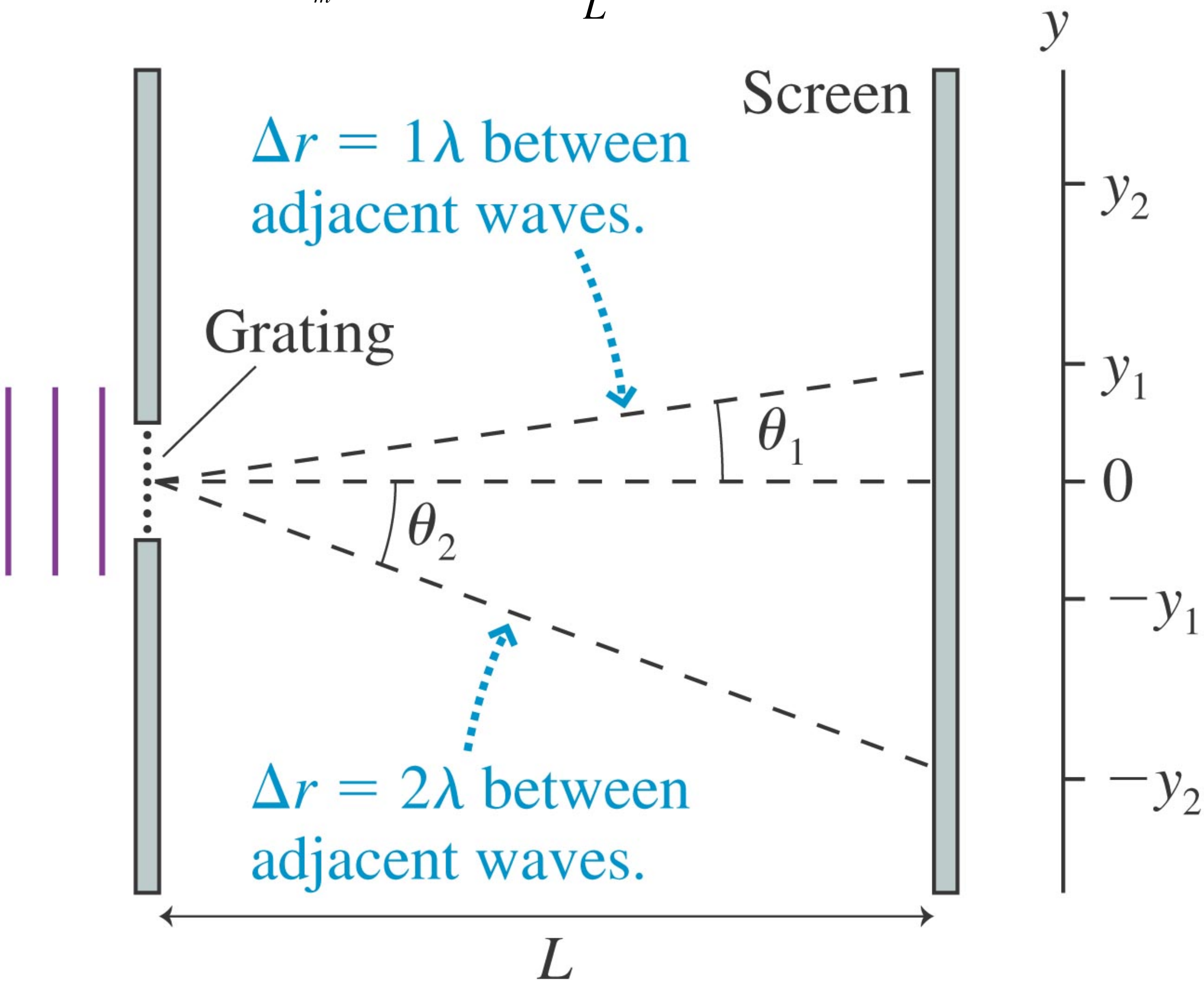
Bright fringes at same angle as for double slit

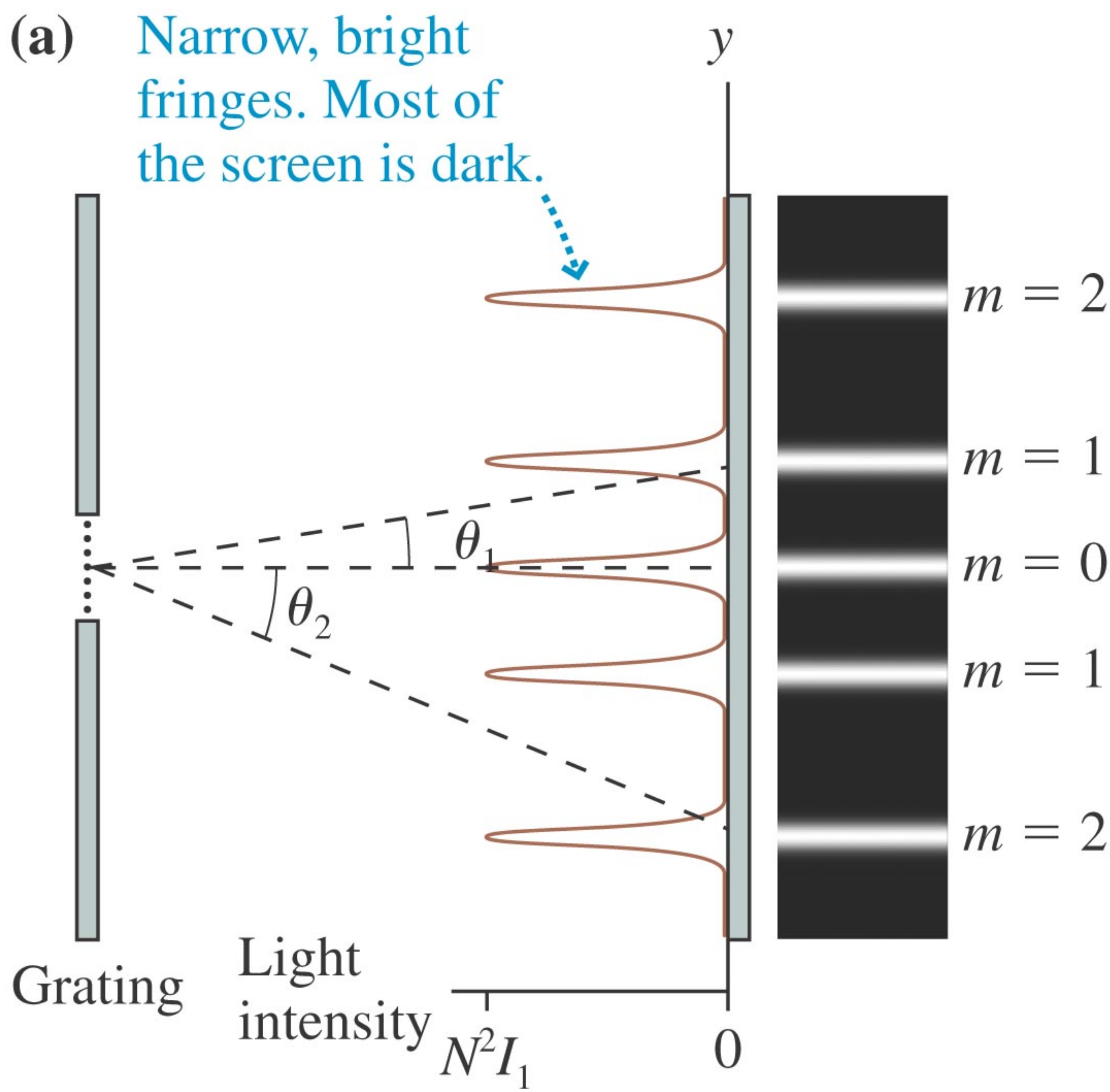
$$m = 0, 1, 2, \ldots$$

$$\sin\theta_m = m\lambda / d$$

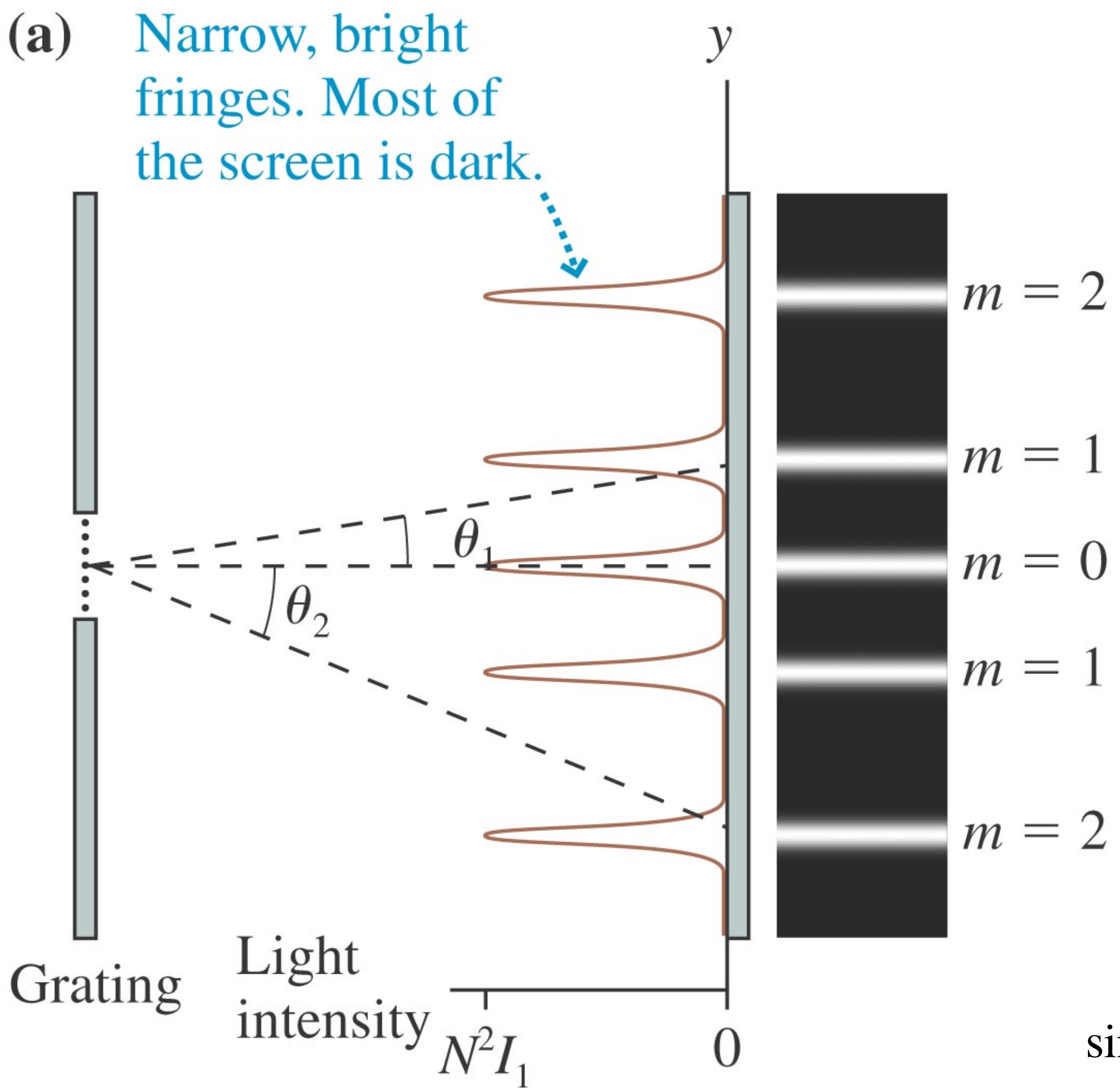
Location of Fringes on distant screen

$$\sin\theta_m = m\lambda / d \qquad \frac{y_m}{L} = \tan\theta_m$$





(a)
Narrow, bright fringes. Most of the screen is dark.
y
m = 2
m = 1
m = 0
m = 1
m = 2
θ1
θ2
Grating
Light intensity
N2I1
0



$$\frac{I_{fringe}}{I_{SA}} = N$$

width of fringe

$$\frac{fringe\ width}{fringe\ spacing} = \frac{1}{N}$$

$$\sin\theta_m = m\lambda / d \qquad \frac{y_m}{L} = \tan\theta_m$$

Measuring Light Spectra

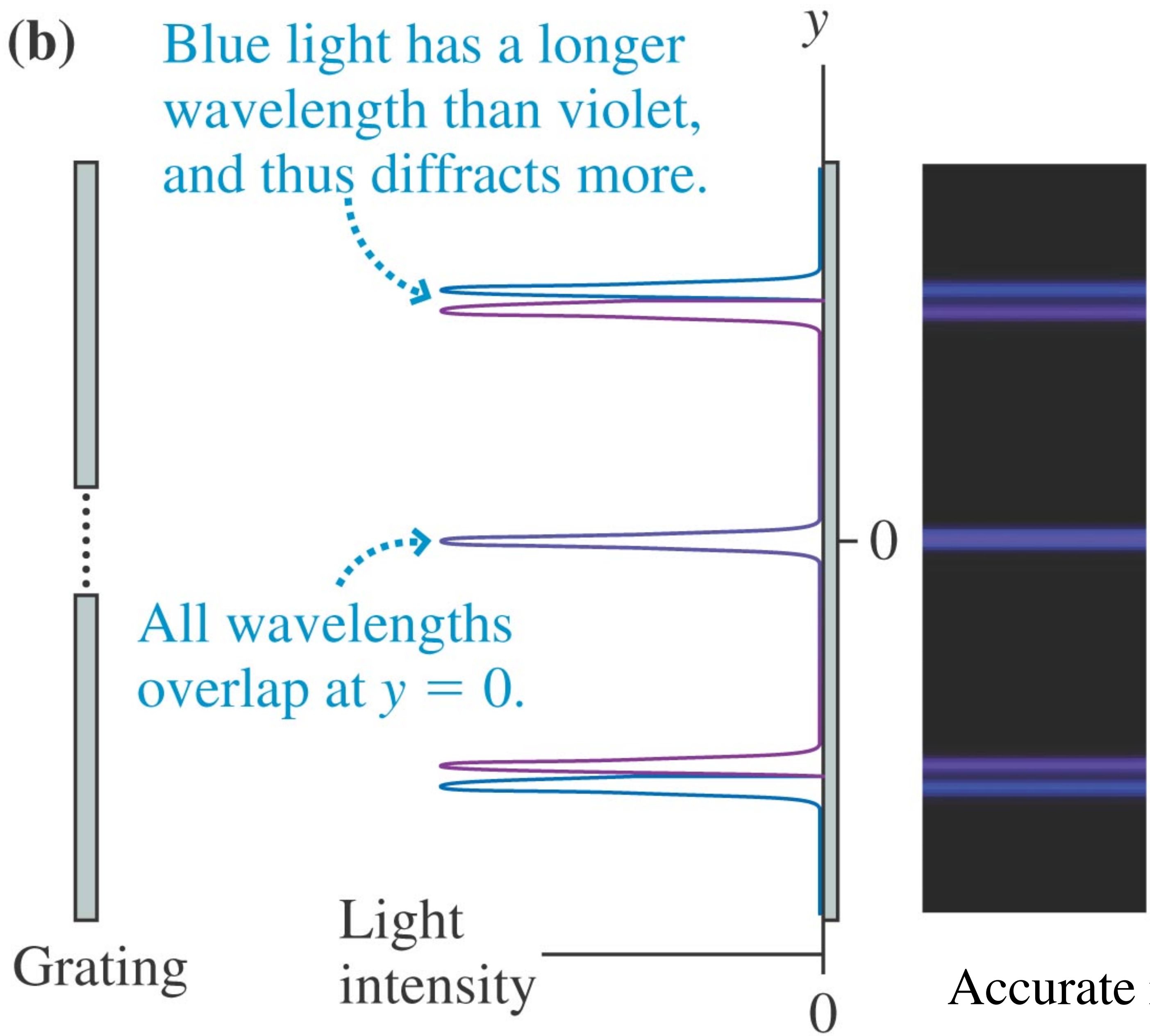
Light usually contains a superposition of many frequencies.

The amount of each frequency is called its spectrum.

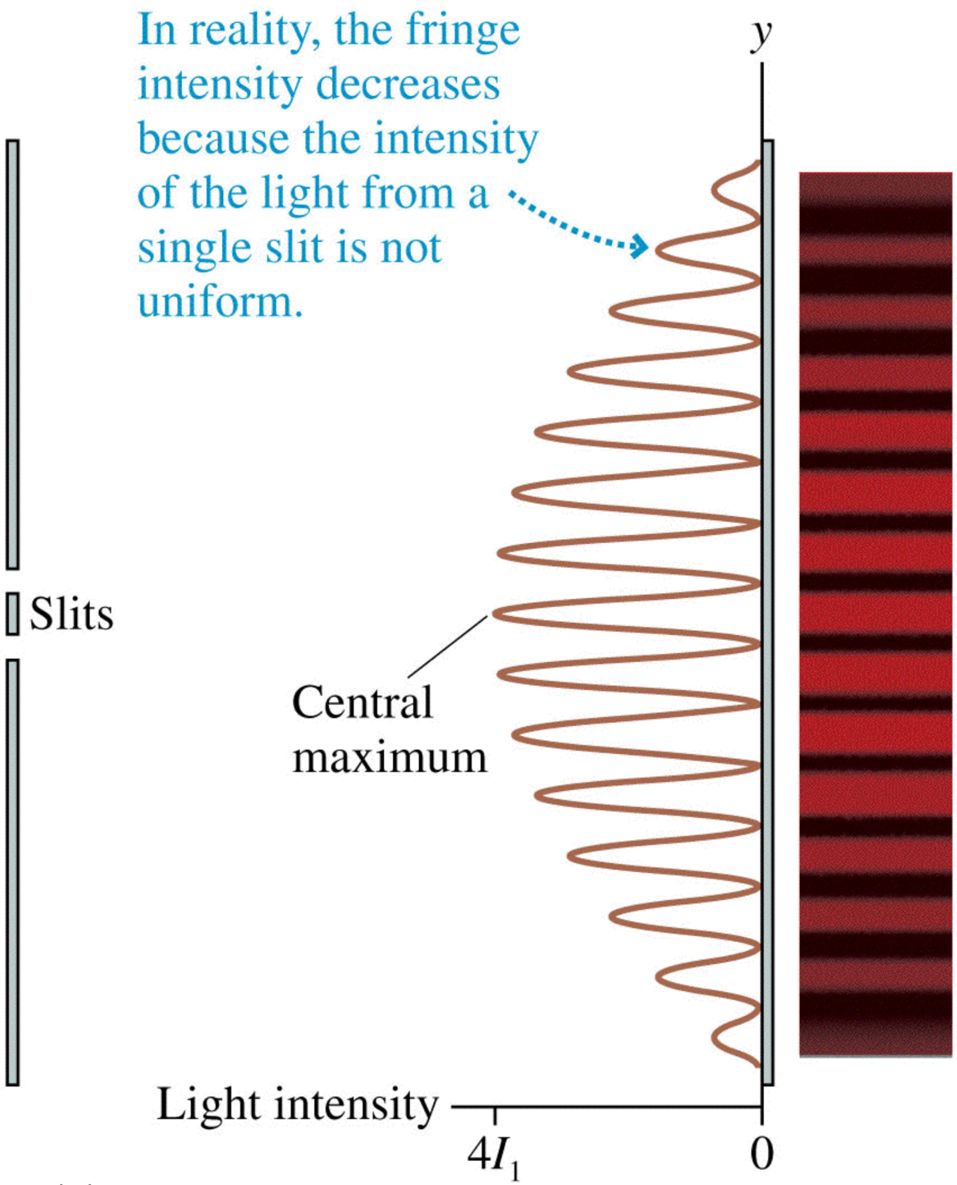
Knowing the components of the spectrum tells us about
the source of light.

Composition of stars is known by measuring the spectrum of their light.

$$\sin\theta_m = m\lambda / d \qquad \frac{y_m}{L} = \tan\theta_m$$

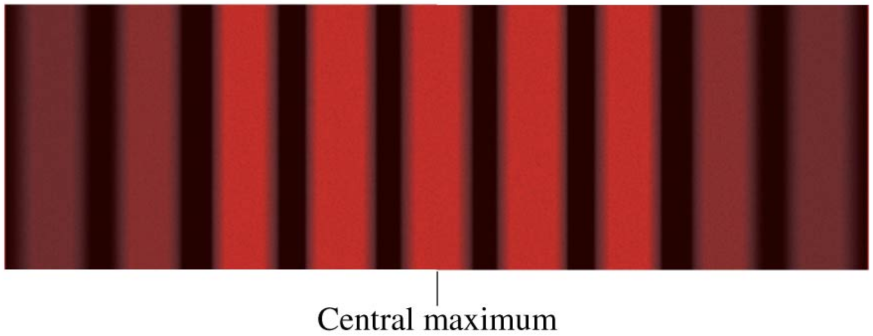


Accurate resolution of spectrum requires many lines



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

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.

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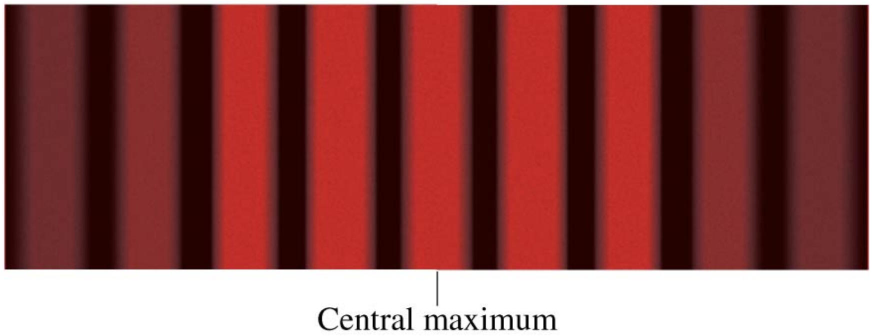
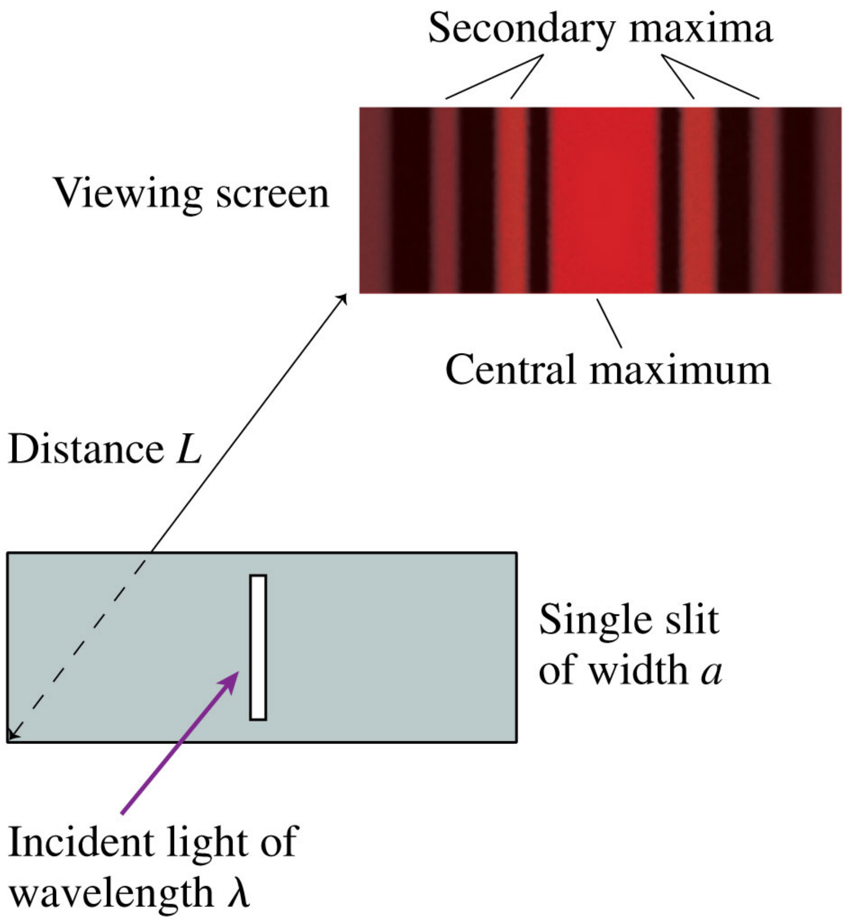


A. $\sqrt{2}$.

B. 2.

✔ **C. 4.**

D. 8.

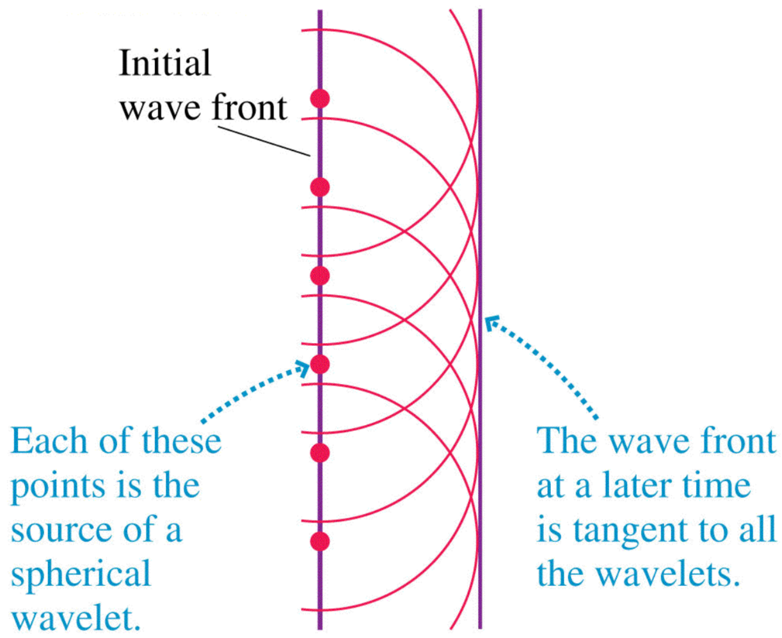


- Diffraction through a tall, narrow slit is known as single-slit diffraction.
- A viewing screen is placed distance L behind the slit of width *a*, and we will assume that $L >> a$.

Huygen's (1629-1695) Principle

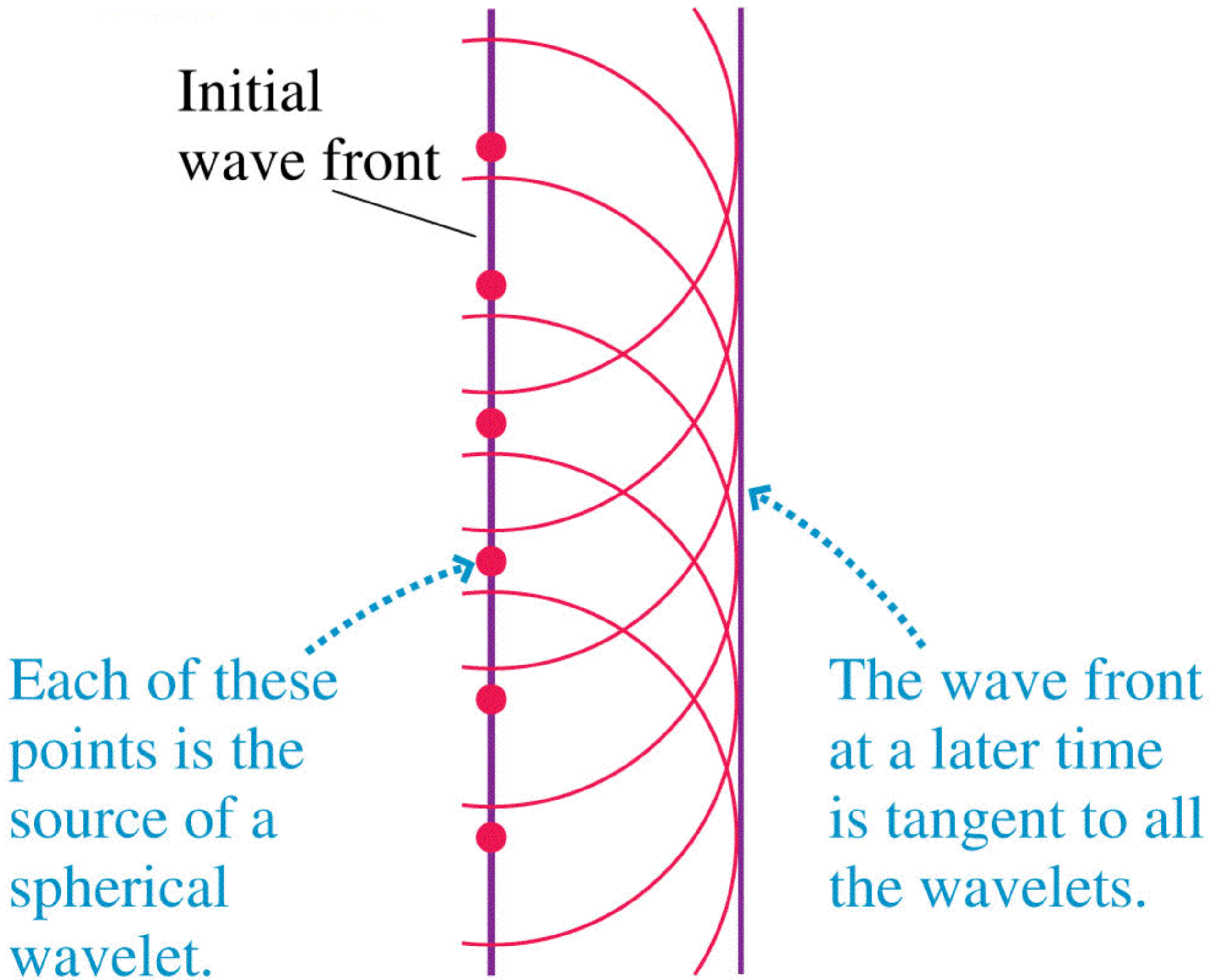
1. Each point on a wave front is the source of a spherical wavelet that spreads out at the wave speed.

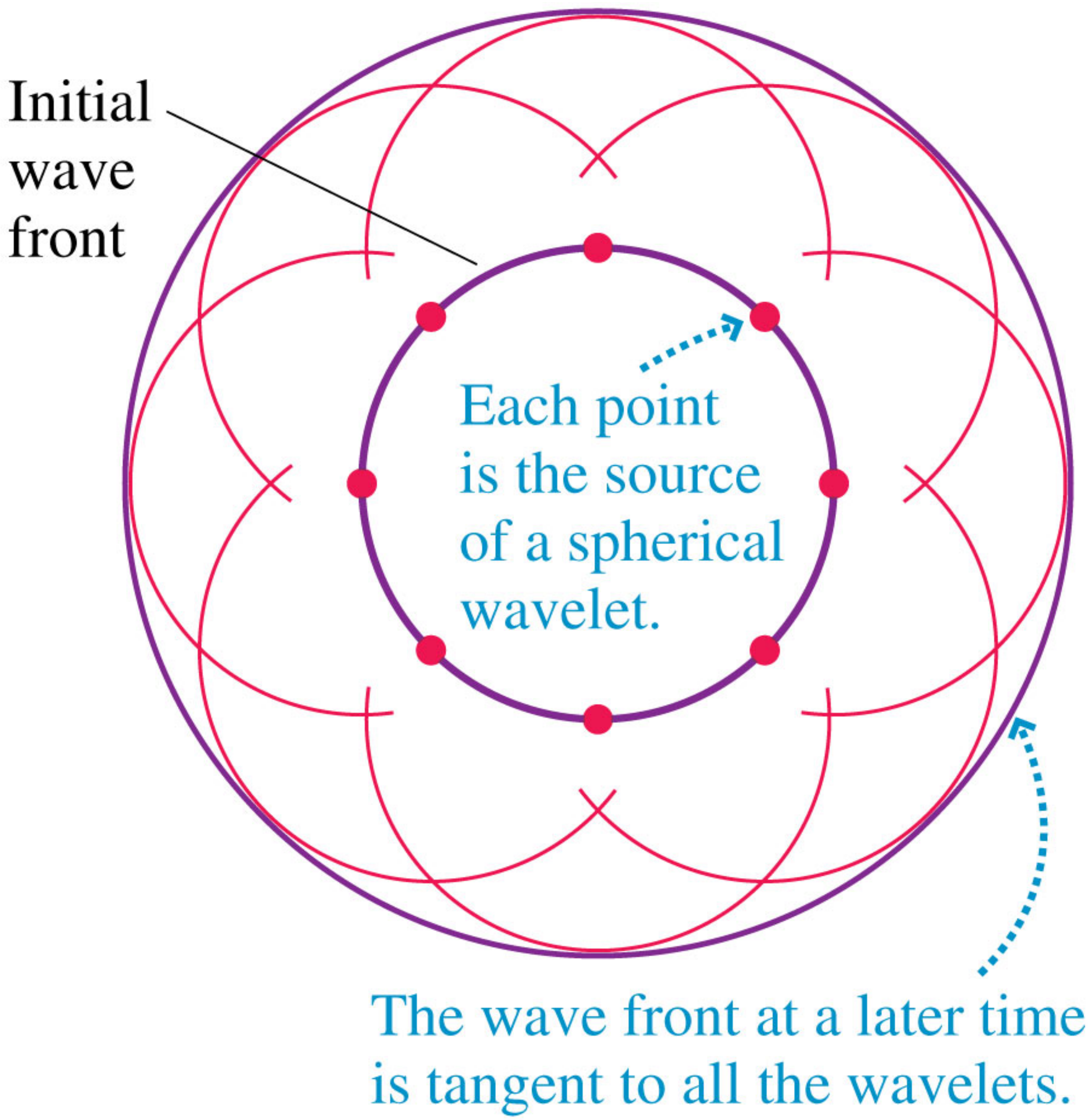
2. At a later time, the shape of the wave front is the line tangent to all the wavelets.



C. Huygens

[Wikimedia Commons]


Initial
wave front
Each of these
points is the
source of a
spherical
wavelet.
The wave front
at a later time
is tangent to all
the wavelets.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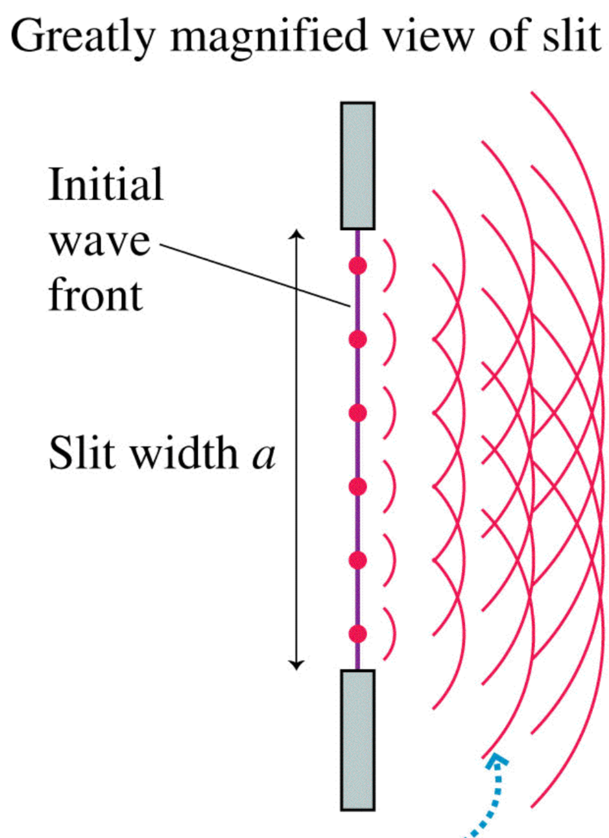
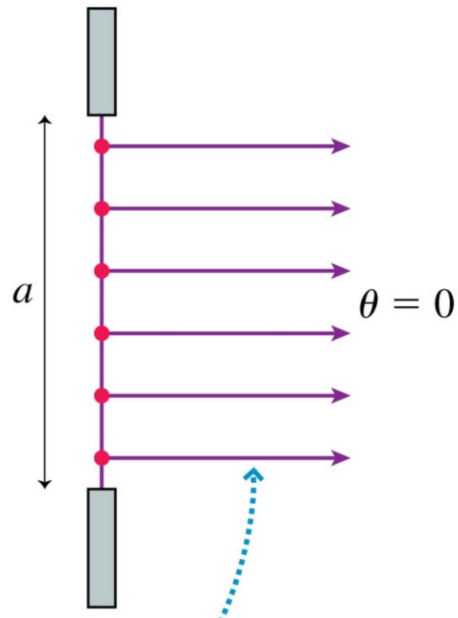


The wavelets from each point on the initial wave front overlap and interfere, creating a diffraction pattern on the screen.

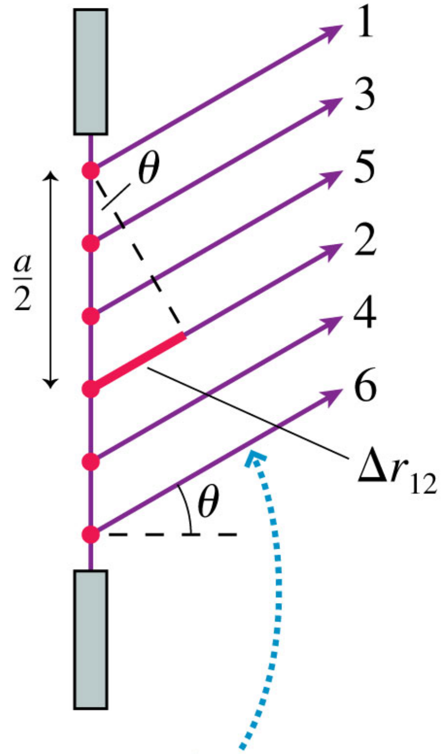
- The figure shows a wave front passing through a narrow slit of width a.
- According to Huygens' principle, each point on the wave front can be thought of as the source of a spherical wavelet.



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.

- 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.

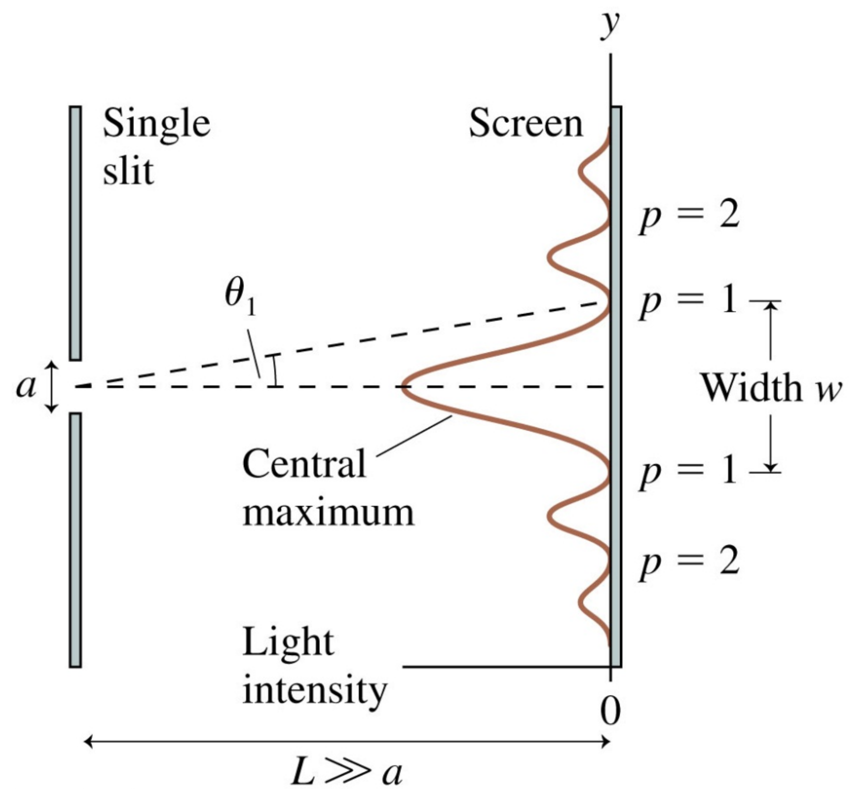
Each point on the wave front is paired with another point distance $a/2$ away.



These wavelets all meet on the screen at angle θ. Wavelet 2 travels distance $\Delta r_{12} = (a/2)\sin\theta$ farther than wavelet 1.

- 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.

- 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:



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

EXAMPLE 22.4 **Diffraction of a laser through a slit**

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

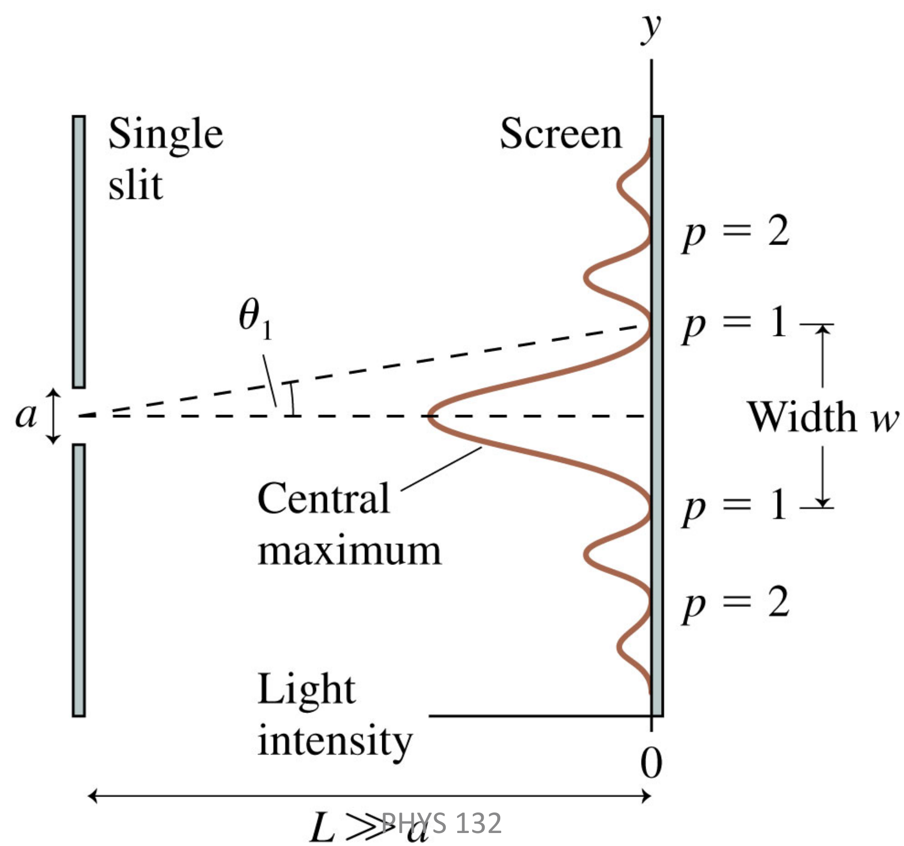
MODEL A narrow slit produces a single-slit diffraction pattern. A displacement of only 1.2 cm in a distance of 200 cm means that angle θ_1 is certainly a small angle.

Whiteboard, TA & LA

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

EXAMPLE 22.4 Diffraction of a laser through a slit

VISUALIZE The intensity pattern will look like the figure below.



EXAMPLE 22.4 Diffraction of a laser through a slit

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

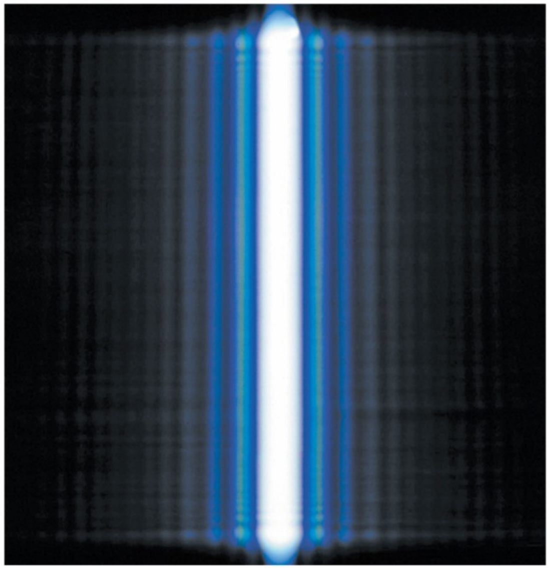
$$\theta_1 = \frac{1.2 \text{ cm}}{200 \text{ cm}} = 0.00600 \text{ rad} = 0.344^\circ$$

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

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

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

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



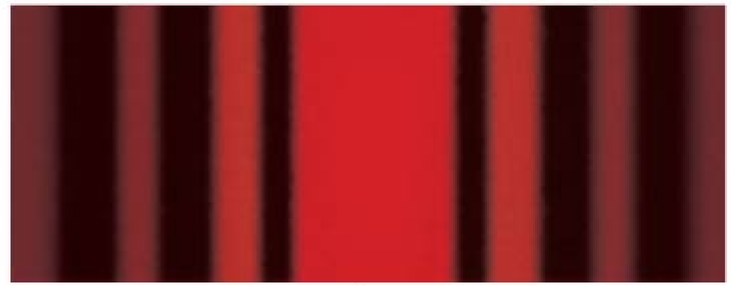
$$w = \frac{2\lambda L}{a} \qquad \text{(single slit)}$$

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

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.

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.

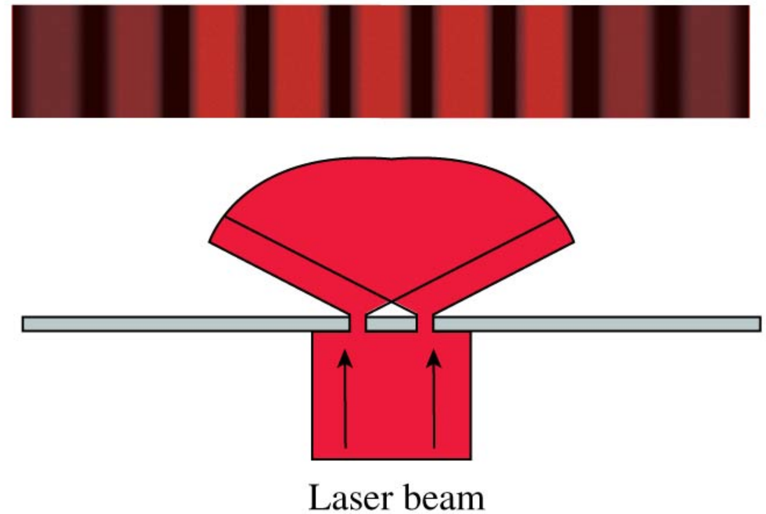
B. In the same positions.

✔ **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 $y_p = \frac{p\lambda L}{a}$.

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



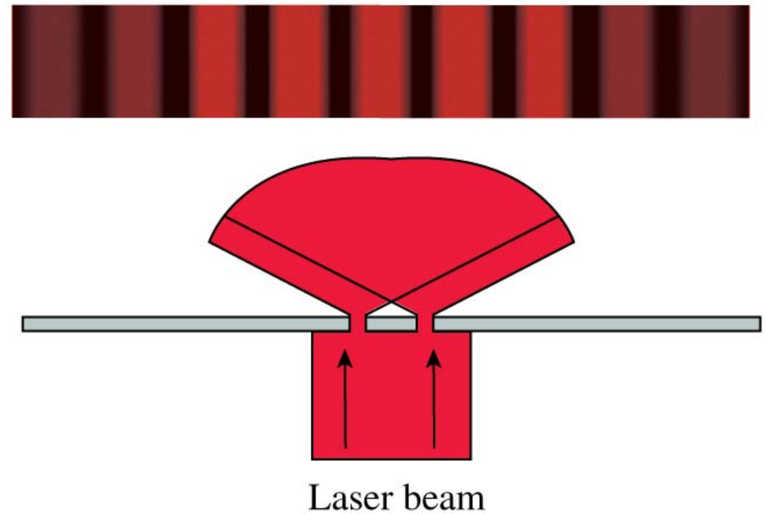
A.


B.


C.


D.


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.** 

The End of Classical Physics

Photon Model of Light

Light comes in chunks called photons,

$$E = hf$$

Energy=Planck's constant x frequency

Wave Model of Particles

$$p = h / \lambda$$

Momentum = Planck's constant/wavelength

Some History

Classical Physics - 1900

Newton's laws of motion + Maxwell's equations for EM fields

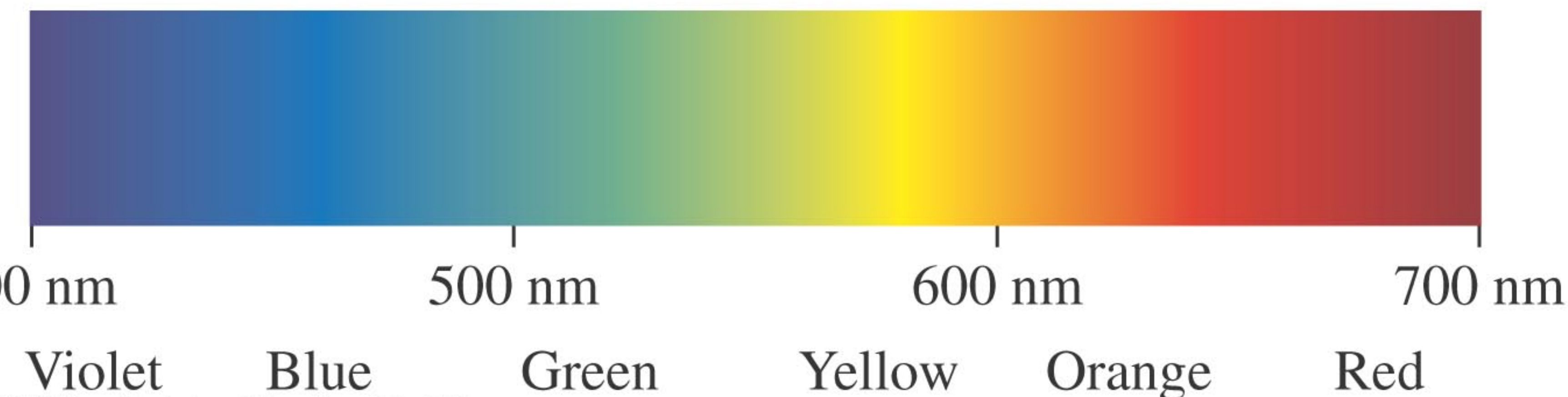
Things it can not explain:

- Discrete spectra of atoms
- Blackbody radiation
- Photo-electric effect
- Existence of atoms
- Diffraction of electrons

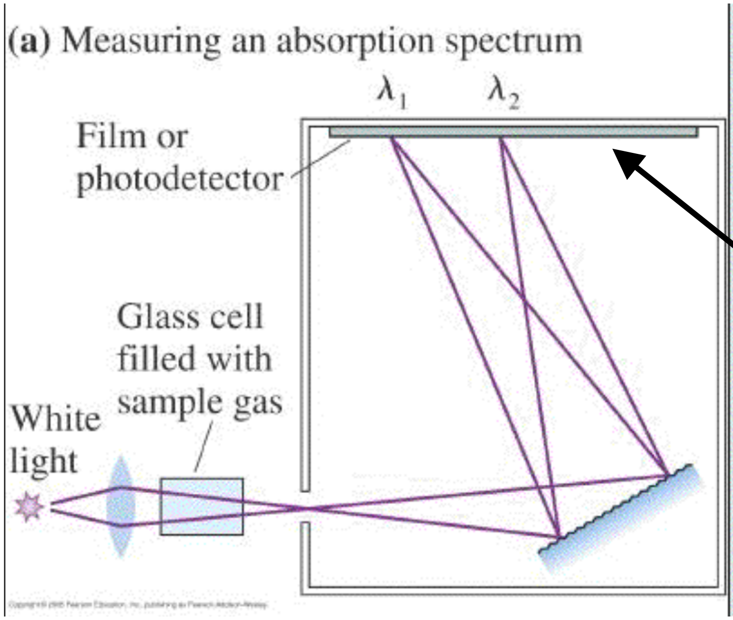
Classical physics was thought to describe the interaction of light with charges until there were discovered too many things that it could not explain.

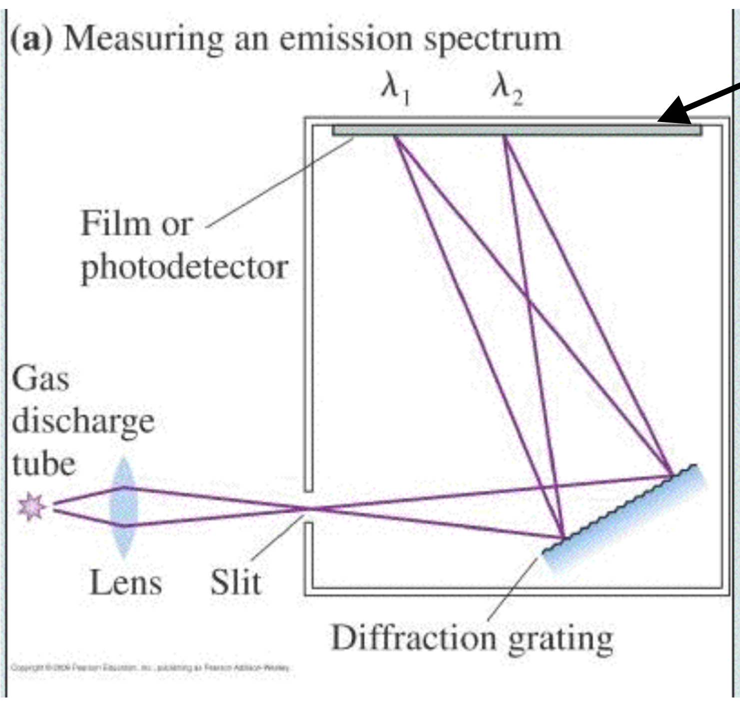
Discrete spectra of atoms - pass light through a diffraction grating

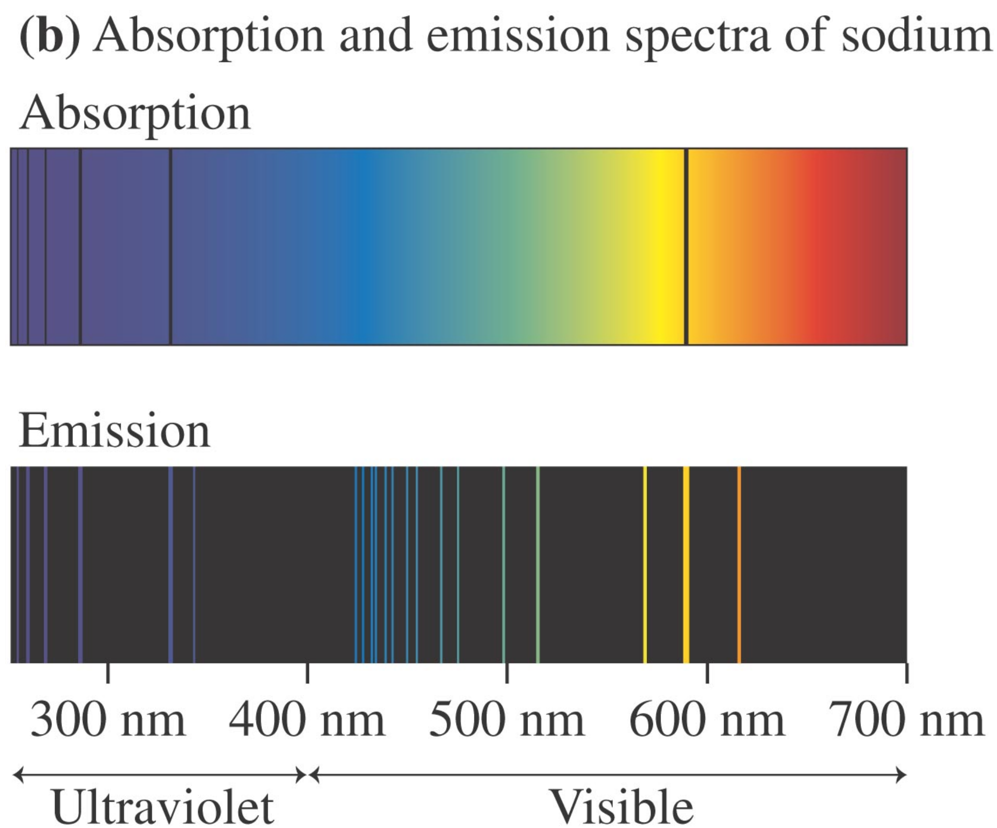
(a) Incandescent lightbulb



(b) Helium

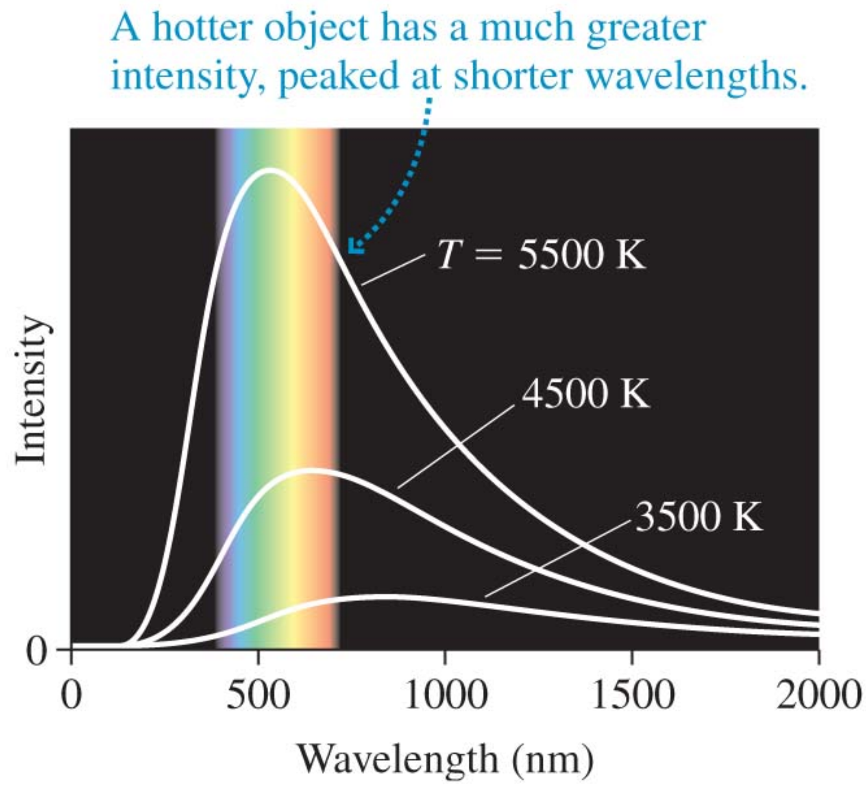

(a) Measuring an absorption spectrum
λ_1
λ_2
Film or photodetector
Glass cell filled with sample gas
White light


(a) Measuring an emission spectrum
λ_1
λ_2
Film or photodetector
Gas discharge tube
Lens
Slit
Diffraction grating


(b) Absorption and emission spectra of sodium
Absorption
Emission
300 nm
400 nm
500 nm
600 nm
700 nm
Ultraviolet
Visible

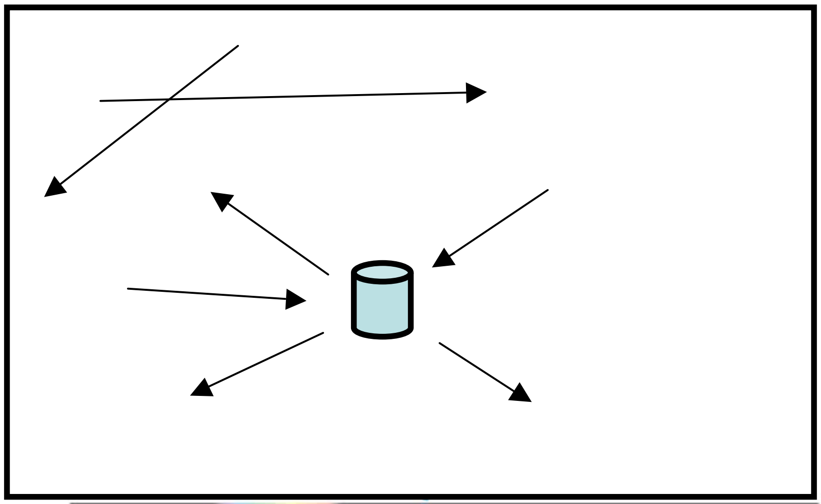
Lava glows when hot -Black Body Radiation

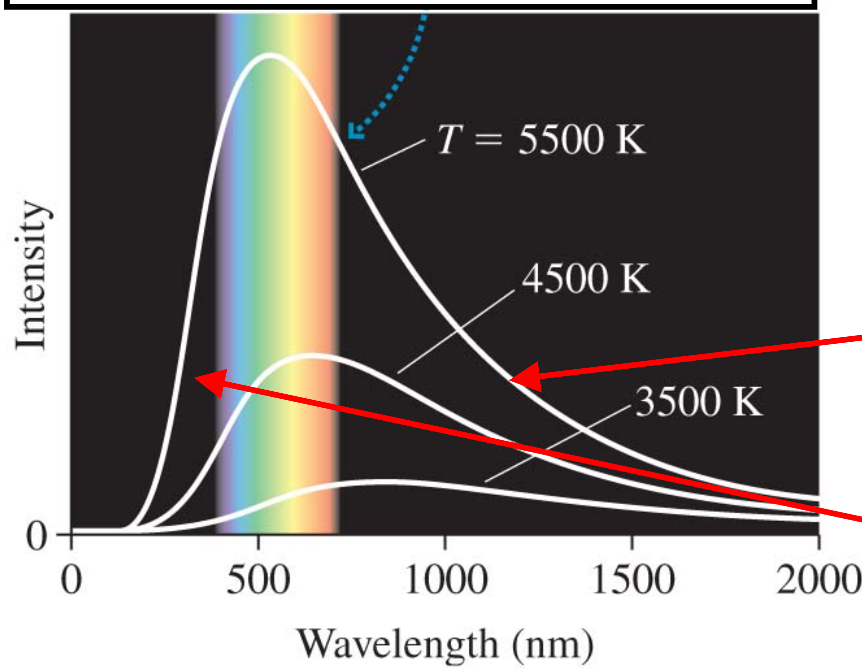
Blackbody Radiation



Objects that radiate continuous spectra have similar spectra. In fact in many cases the shape of the spectrum depends only on the temperature of the body.

Box with object at temperature T and photons





Assume the walls of the box are perfectly reflecting and the object is perfectly absorbing.

In thermodynamic equilibrium the distribution of light can only depend on the temperature of the object.

Whatever rate light is absorbed, an equal amount must be emitted at the same rate.

Planck introduced his constant to explain the small wavelength cut-off

Can treat photons as classical fields

$\frac{1}{2}kT$ in each mode of the cavity

Must treat photons as photons, need h

$$\frac{1}{2}kT < hf = hc/\lambda$$

Quantum Mechanics:

Basic Idea

Sometimes particles of matter behave as if they were some kind of wave.

Sometimes electromagnetic waves (light) behave as if they were composed of particles (photons)

In both cases an element of probability is introduced. We can no longer say what will happen in a set of circumstances, rather we can say what are the probabilities of various things happening.

The **photon model** of light consists of three basic postulates:

1. Light consists of discrete, massless units called *photons*. A photon travels in vacuum at the speed of light.
2. Each photon has energy:

$$E_{\text{photon}} = hf$$

   where f is the frequency of the light and $h = 6.63 \times 10^{-34}\ \text{J s}$ is Planck's constant. In other words, the light comes in discrete "chunks" of energy hf.
3. The superposition of a sufficiently large number of photons has the characteristics of a classical light wave.

The Photon Model

- When it interacts with matter, light behaves as if it consisted of packets (photons) that carry both energy and momentum according to:

$$E = hf = \frac{hc}{\lambda} \qquad p = \frac{E}{c} = \frac{h}{\lambda}$$

with hc = 1234 eV-nm.

  – These equations are somewhat peculiar. The left side of the equations look like particle properties and the right side like wave properties.

Does a photon of red light have more energy or less energy than a photon of blue light?

A. More energy
B. Less energy

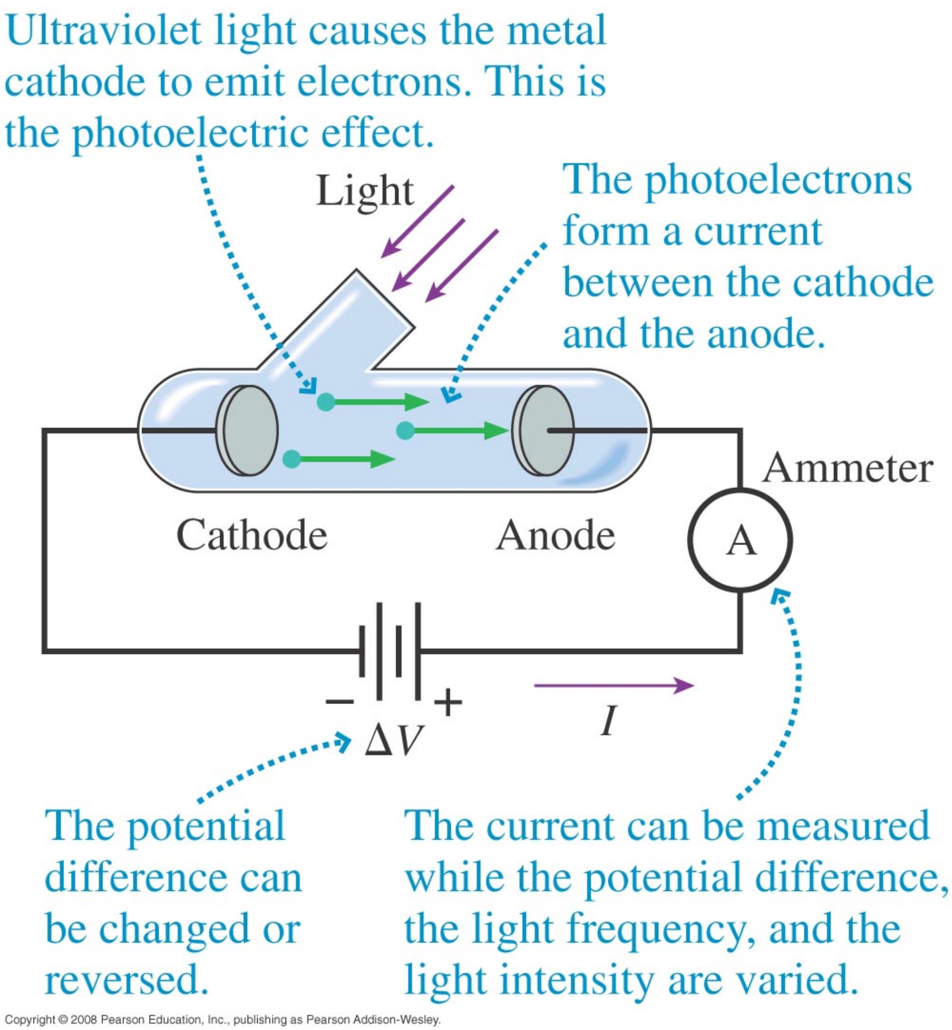
Does a photon of red light have more energy or less energy than a photon of blue light?

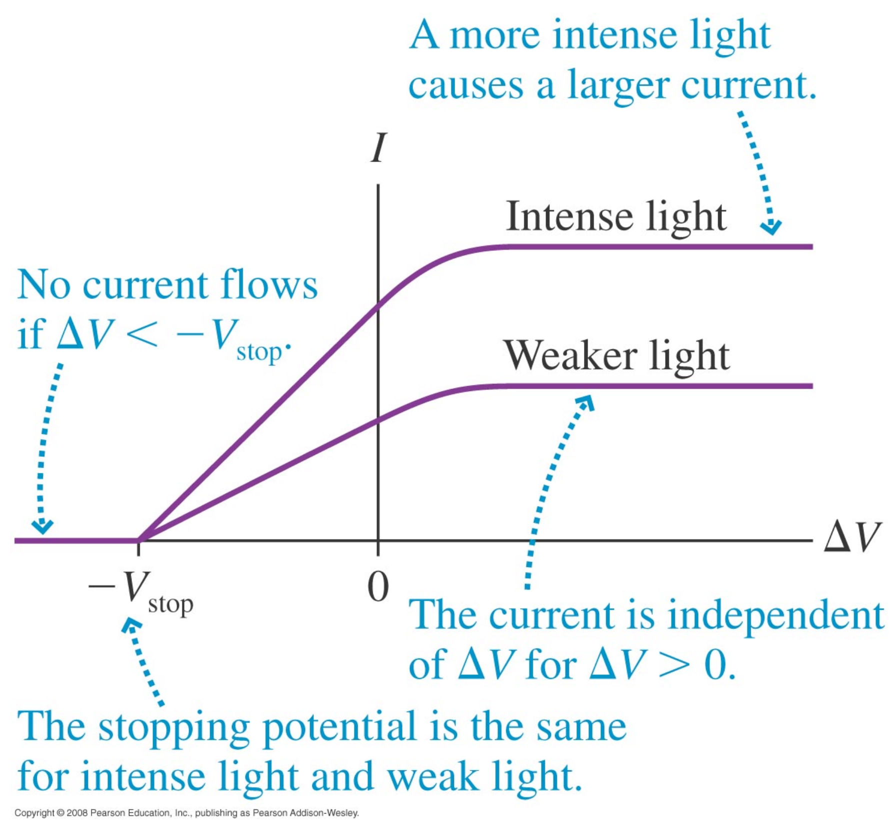
A. More energy

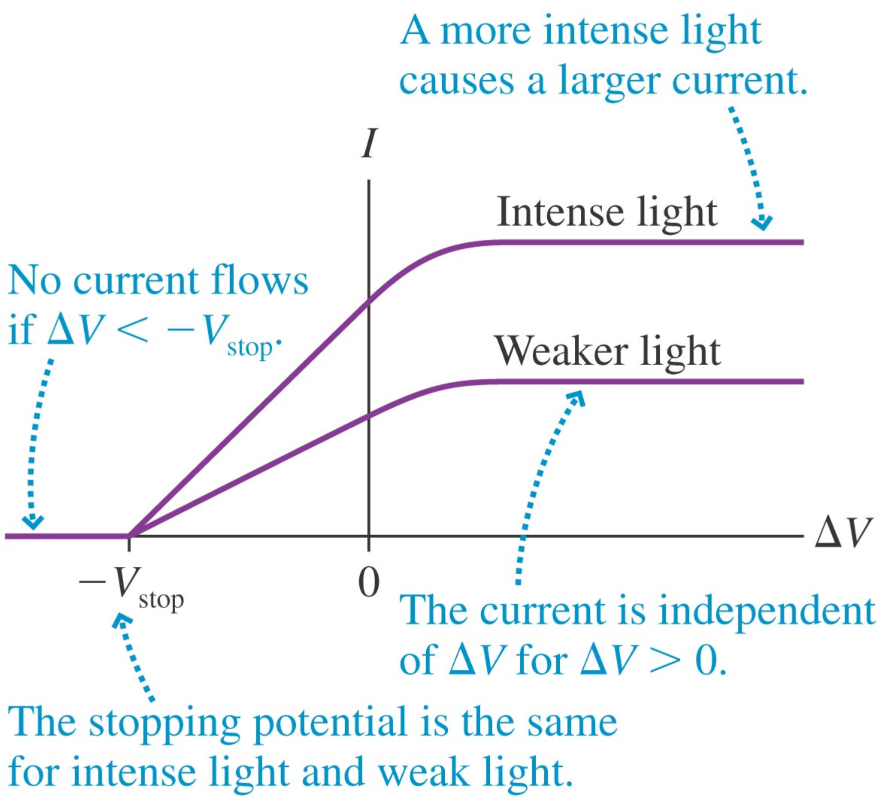
✔ **B. Less energy**

Light appears to come in chunks - particle like

Made clear by Einstein's explanation of the photoelectric effect.







V_{stop} depends on frequency of light

Planck's Constant

$$h = 6.63 \times 10^{-34} \text{ Joule-seconds}$$

Einstein showed that this behavior could be explained if:

1. Light consists of discrete massless units called photons.
2. Each Photon has energy $E_{photon} = hf$.
3. Many photons together act like the continuous field predicted by Maxwell's equations.

Foothold Ideas: The Photon Model

- When it interacts with matter, light behaves as if it consisted of packets (photons) that carry both energy and momentum according to:

$$E = hf = \frac{hc}{\lambda} \qquad p = \frac{E}{c} = \frac{h}{\lambda}$$

with hc = 1234 eV-nm.

  – These equations are somewhat peculiar. The left side of the equations look like particle properties and the right side like wave properties.

EXAMPLE:The energy of a photon

QUESTIONS:

EXAMPLE 25.2 The energy of a photon

550 nm is the average wavelength of visible light.

a. What is the energy of a photon with a wavelength of 550 nm?

b. A typical incandescent lightbulb emits about 1 J of visible light energy every second. Estimate the number of photons emitted per second.

Whiteboard, TA & LA

EXAMPLE 25.2 The energy of a photon

SOLVE a. The frequency of the photon is

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8 \text{ m/s}}{550 \times 10^{-9} \text{ m}} = 5.4 \times 10^{14} \text{ Hz}$$

Equation 25.4 gives us the energy of this photon:

$$E_{\text{photon}} = hf = (6.63 \times 10^{-34} \text{ J s})(5.4 \times 10^{14} \text{ Hz}) = 3.6 \times 10^{-19} \text{ J}$$

This is an extremely small energy!

EXAMPLE 25.2 The energy of a photon

b. The photons emitted by a lightbulb span a range of energies because the light spans a range of wavelengths, but the *average* photon energy corresponds to a wavelength near 550 nm. Thus we can estimate the number of photons in 1 J of light as

$$N \approx \frac{1\text{ J}}{3.6 \times 10^{-19}\text{ J/photon}} \approx 3 \times 10^{18}\text{ photons}$$

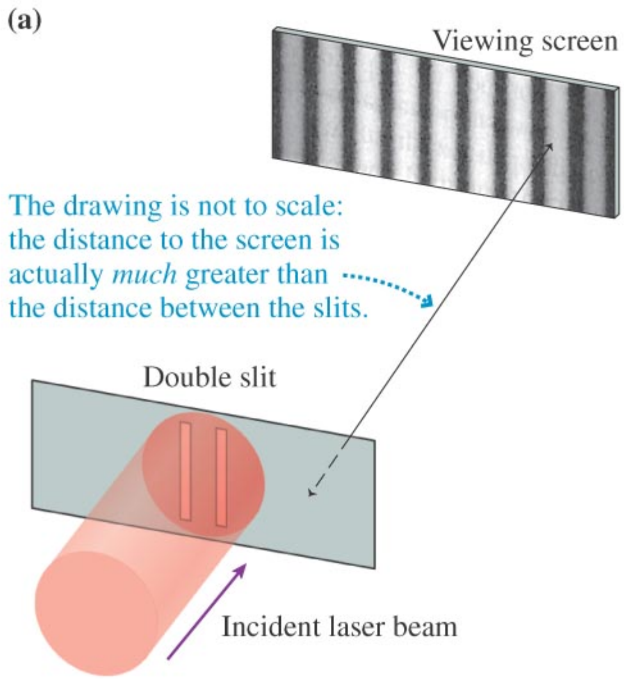
A lightbulb emits about 3×10^{18} photons every second.

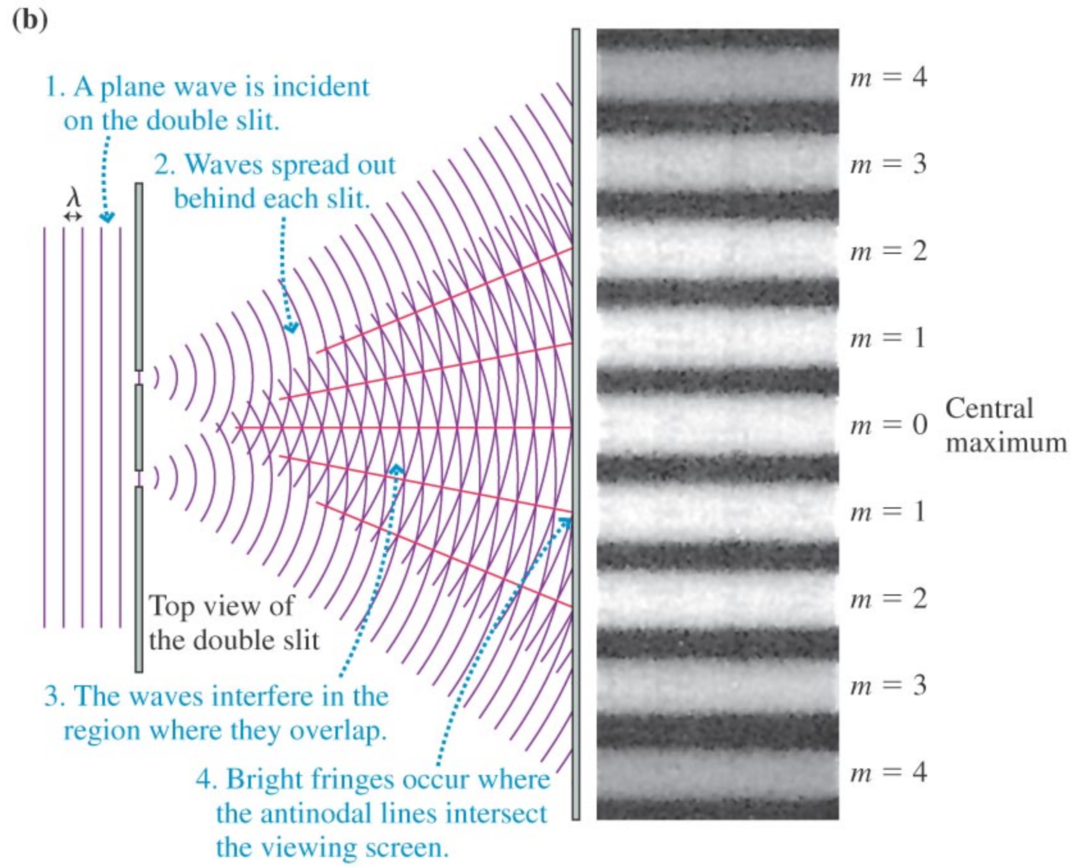
EXAMPLE 25.2 The energy of a photon

ASSESS This is a staggeringly large number. It's not surprising that in our everyday life we would sense only the river and not the individual particles within the flow.

Interference of light
Double Slit experiment

Coherence because sources are at exactly the same frequency





What happens when individual photons pass through the slit?

Double-Slit Experiment with Photons