Interference of Light waves

A. Karle
Physics 202
Dec. 4, 2007
Chapter 37 and Chapter 38.1-3

- PART I
  - 37.1 Introduction
  - 37. 2 Double slit
  - 37. 3 (maxima, minima, high level only)
  - 37. 5 Phase change,
  - 37. 6 Interference on thin films
  - 37. 7 Applications, Michelson interferometer

Wave Optics

- Wave optics is a study concerned with phenomena that cannot be adequately explained by geometric (ray) optics
- These phenomena include:
  - Interference
  - Diffraction
  - Polarization

Interference

- In *constructive interference* the amplitude of the resultant wave is greater than that of either individual wave
- In *destructive interference* the amplitude of the resultant wave is less than that of either individual wave
- All interference associated with light waves arises when the electromagnetic fields that constitute the individual waves combine

Conditions for Interference

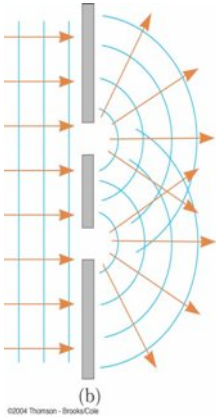
- To observe interference in light waves, the following two conditions must be met:
  1) The sources must be **coherent**
     - They must maintain a constant phase with respect to each other
  2) The sources should be **monochromatic**
     - Monochromatic means they have a single wavelength

Producing Coherent Sources

- Light from a monochromatic source is used to illuminate a barrier
- The barrier contains two narrow slits
  - The slits are small openings
- The light emerging from the two slits is coherent since a single source produces the original light beam
- This is a commonly used method

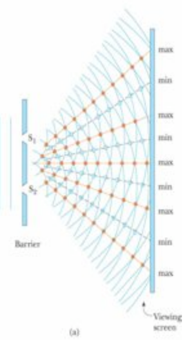
Diffraction

- From Huygens's principle we know the waves spread out from the slits
- This divergence of light from its initial line of travel is called **diffraction**



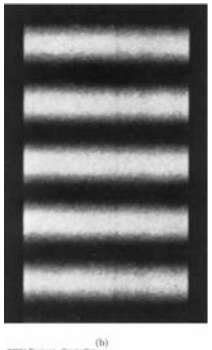
Young's Double-Slit Experiment: Schematic

- Thomas Young first demonstrated interference in light waves from two sources in 1801
- The narrow slits S_1 and S_2 act as sources of waves
- The waves emerging from the slits originate from the same wave front and therefore are always in phase

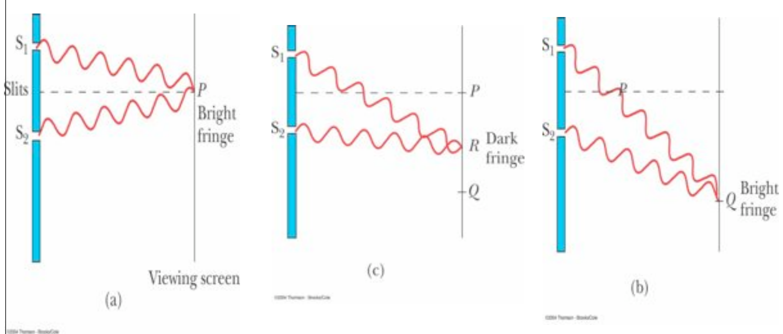


Resulting Interference Pattern

- The light from the two slits forms a visible pattern on a screen
- The pattern consists of a series of bright and dark parallel bands called *fringes*
- *Constructive interference* occurs where a bright fringe occurs
- *Destructive interference* results in a dark fringe



Interference Patterns



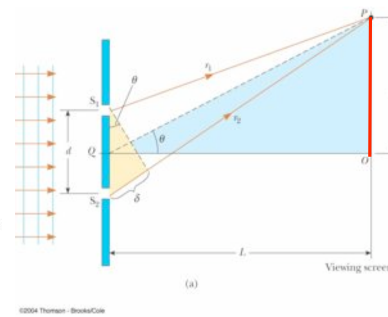
Interference Equations

- For bright fringes

$$y_{\text{bright}} = \frac{\lambda L}{d} m \quad (m = 0, \pm 1, \pm 2 \ldots)$$

- For dark fringes

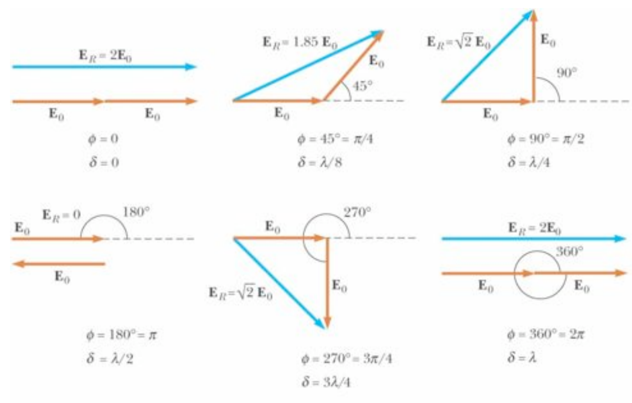
$$y_{\text{dark}} = \frac{\lambda L}{d}\left(m + \frac{1}{2}\right) \quad (m = 0, \pm 1, \pm 2 \ldots)$$



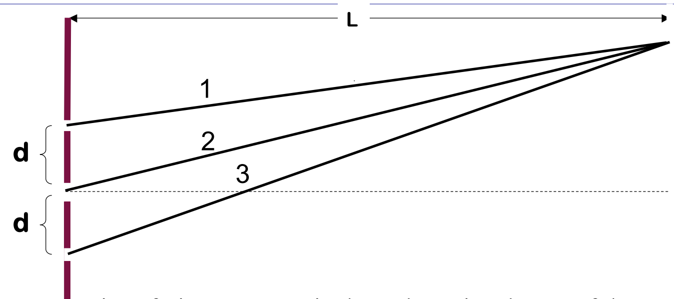
Uses for Young's Double-Slit Experiment

- Young's double-slit experiment provides a method for measuring wavelength of the light
- This experiment gave the wave model of light a great deal of credibility
  - It was inconceivable that particles of light could cancel each other in a way that would explain the dark fringes

Phasor Diagrams for Two Coherent Sources, Diagrams



Constructive Interference 3 Rays

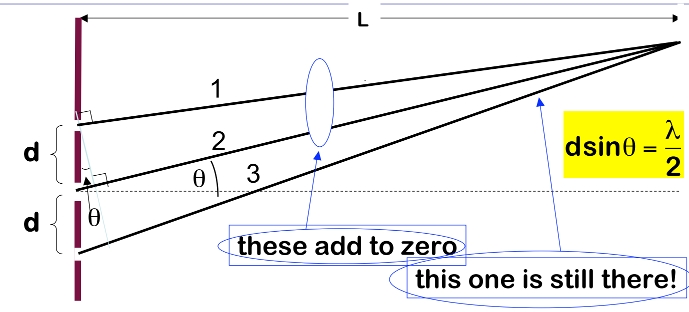


All 3 rays are interfering constructively at the point shown. If the intensity from ray 1 is I_0 , what is the combined intensity of all 3 rays?

1) I_0 2) 3 I_0 3) 9 I_0

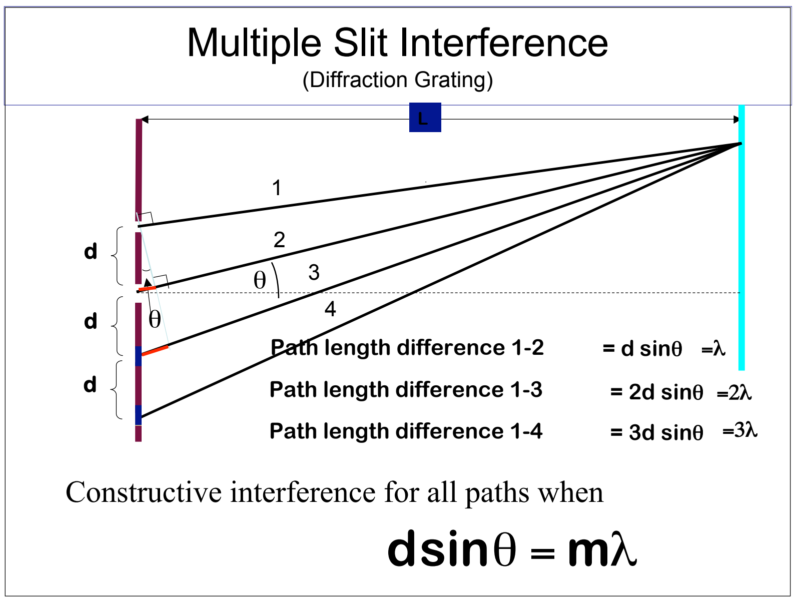
Each slit contributes amplitude E_o at screen. $E_{tot} = 3 E_o$.
But $I \alpha E^2$. $I_{tot} = (3E_0)^2 = 9 E_0^2 = 9 I_0$

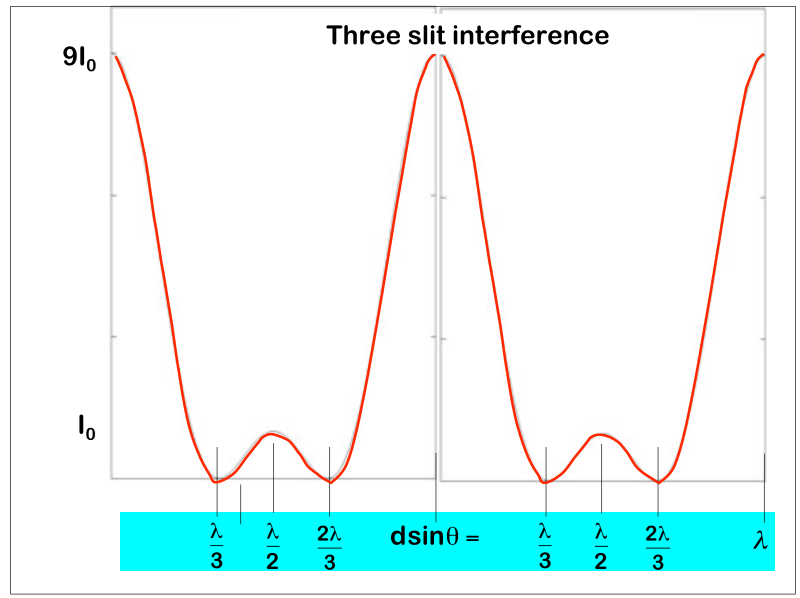
Destructive Interference 3 Rays



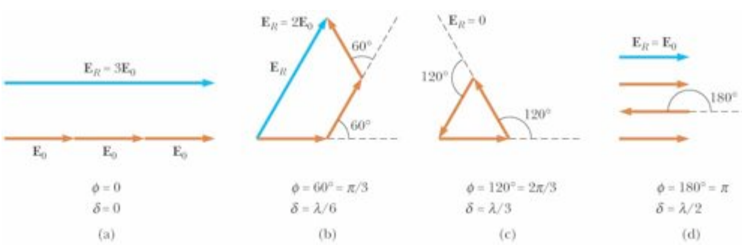
When rays 1 and 2 are interfering destructively, is the intensity from the **three** rays a minimum? 1) Yes 2) No

Rays 1 and 2 completely cancel, but ray 3 is still there.
Expect intensity I = 1/9 I_{max}


Multiple Slit Interference
(Diffraction Grating)
L
1
2
3
4
d
d
d
θ
θ
Path length difference 1-2 = d sinθ =λ
Path length difference 1-3 = 2d sinθ =2λ
Path length difference 1-4 = 3d sinθ =3λ
Constructive interference for all paths when
dsinθ = mλ

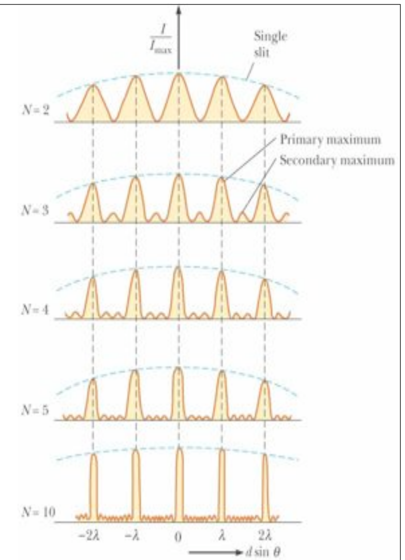

Three slit interference
9I0
I0
dsinθ =
λ/3
λ/2
2λ/3
λ/3
λ/2
2λ/3
λ

Three Slits, Phasor Diagrams



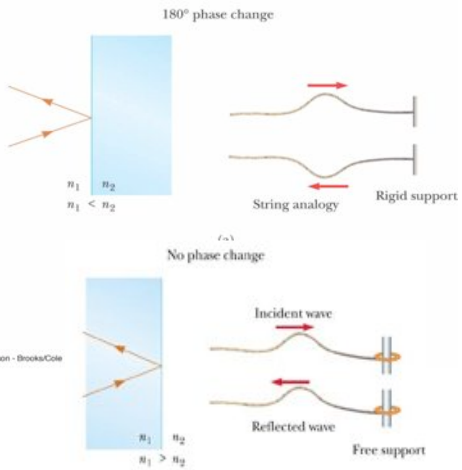
Multiple-Slits, Intensity Graphs

- The primary maxima are nine times more intense than the secondary maxima
  - The intensity varies as E_R^2
- For *N* slits, the primary maxima is N^2 times greater than that due to a single slit



Phase Changes Due To Reflection

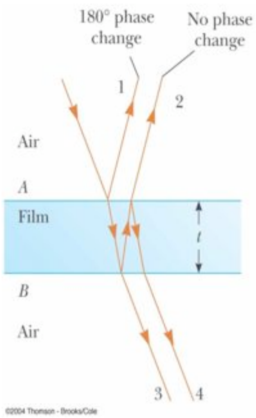
- Case 1:
  - $n_2 > n_1$
  - phase change of 180°



- Case 2:
  - $n_2 < n_1$
  - No phase change

Interference in Thin Films

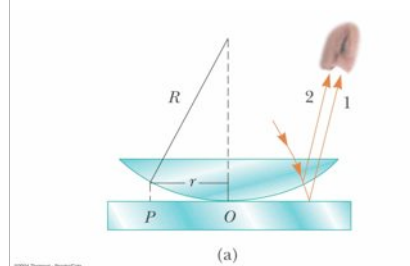
- Ray 1: phase change of 180°
- Ray 2: no phase change
- Ray 2 also travels an additional distance of 2*t* before the waves recombine
- For constructive interference
  - $2nt = (m + 1/2)\lambda$ (m = 0, 1, 2 …)
- For destructive interference
  - $2nt = m\lambda$ (m = 0, 1, 2 …)

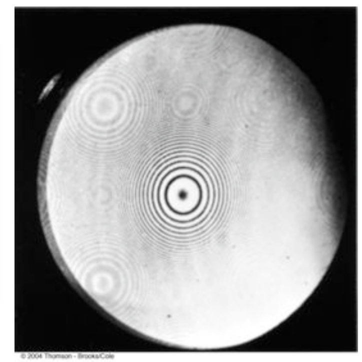


Interference in Thin Films

- If the thin film is between two different media, one of lower index than the film and one of higher index, the conditions for constructive and destructive interference are *reversed*
- With different materials on either side of the film, you may have a situation in which there is a 180° phase change at both surfaces or at neither surface
  - Be sure to check both the path length and the phase change

Newton's Rings, Set-Up and Pattern



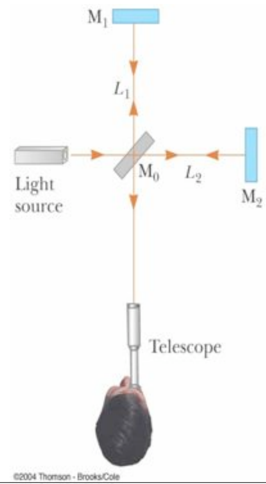


Michelson Interferometer

- The interferometer was invented by an American physicist, A. A. Michelson
- The interferometer splits light into two parts and then recombines the parts to form an interference pattern
- The device can be used to measure wavelengths or other lengths with great precision

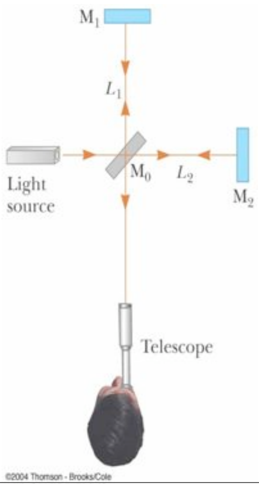
Michelson Interferometer, Schematic

- A ray of light is split into two rays by the mirror M_o
  - The mirror is at 45° to the incident beam
  - The mirror is called a *beam splitter*
- It transmits half the light and reflects the rest



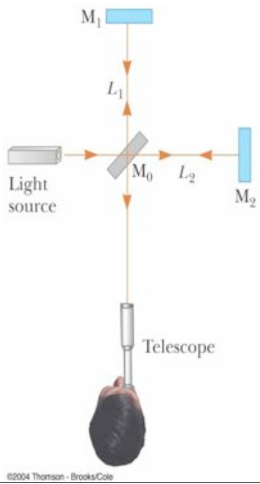
Michelson Interferometer, Schematic Explanation, cont.

- The reflected ray goes toward mirror M_1
- The transmitted ray goes toward mirror M_2
- The two rays travel separate paths L_1 and L_2
- After reflecting from M_1 and M_2, the rays eventually recombine at M_o and form an interference pattern



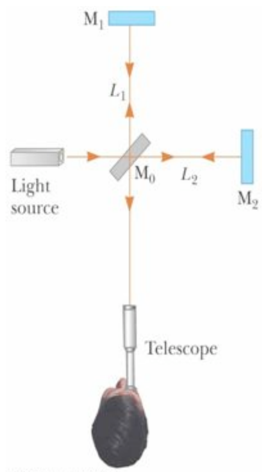
Michelson Interferometer – Operation

- The interference condition for the two rays is determined by their path length difference
- M_1 is moveable
- As it moves, the fringe pattern collapses or expands, depending on the direction M_1 is moved
- The fringe pattern shifts by one-half fringe each time M_1 is moved a distance $\lambda/4$
- The wavelength of the light is then measured by counting the number of fringe shifts for a given displacement of M_1



Michelson Interferometer – Applications

- The Michelson interferometer was used to disprove the idea that the Earth moves through an ether
- One modern application is:
  - Laser Interferometer Gravitational-Wave Observatory (LIGO)



Laser Interferometer Gravitational-Wave Observatory

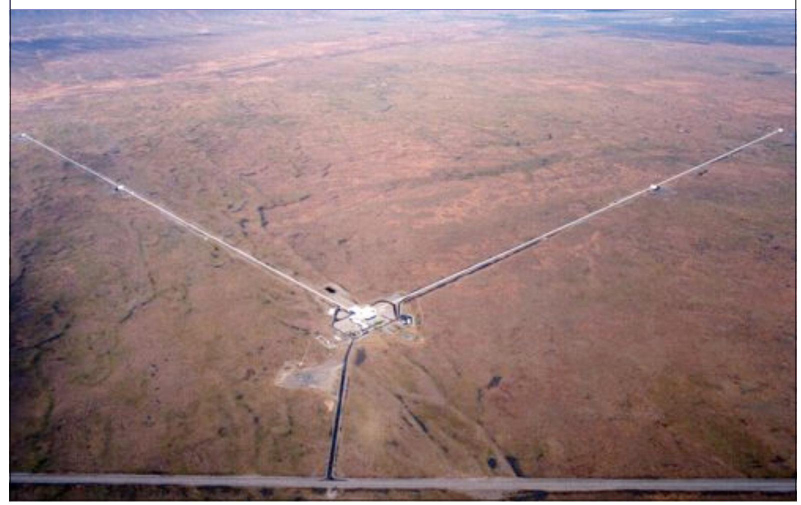
- General relativity predicts the existence of gravitational waves
- In Einstein's theory, gravity is equivalent to a distortion of space
  - These distortions can then propagate through space
- The LIGO apparatus is designed to detect the distortion produced by a disturbance that passes near the Earth

LIGO

- The interferometer uses laser beams with an effective path length of several kilometers
- At the end of an arm of the interferometer, a mirror is mounted on a massive pendulum
- When a gravitational wave passes, the pendulum moves, and the interference pattern due to the laser beams from the two arms changes

- Relative resolution for a change in length: 10^{-18}m, that is about the size of an electron (10^{-8} of the size of an atom) per km.

LIGO in Richland, Washington

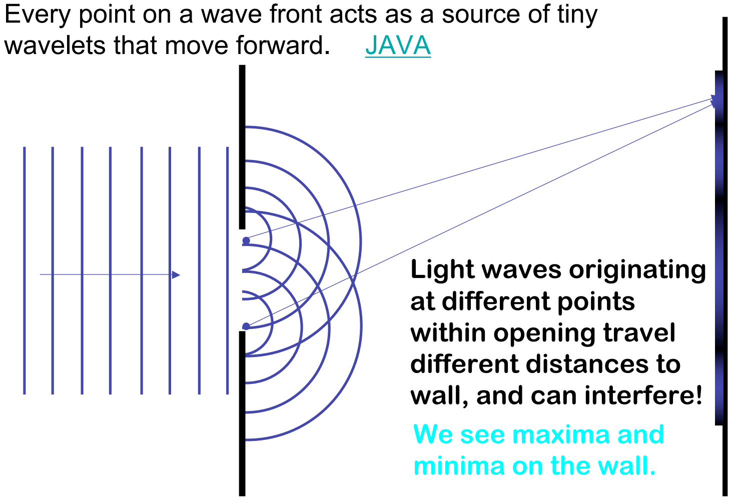


Diffraction, topics from Ch. 38

- PART II
- Chapter 38:
  - 38.1 Introduction
  - 38.2 (without phasor diagrams)
  - 38.3
  - (use Lecture and homework problems as reference to define material for exam)

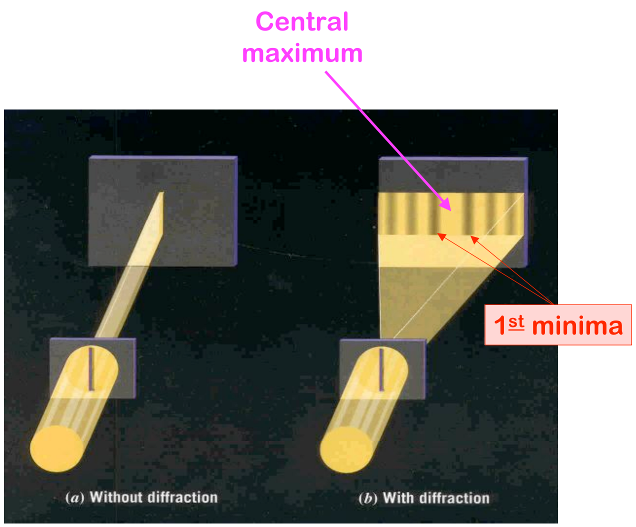
Diffraction/ Huygens

Every point on a wave front acts as a source of tiny wavelets that move forward. JAVA



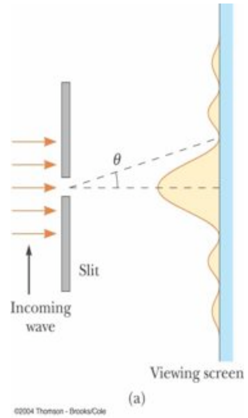
Light waves originating at different points within opening travel different distances to wall, and can interfere!

We see maxima and minima on the wall.



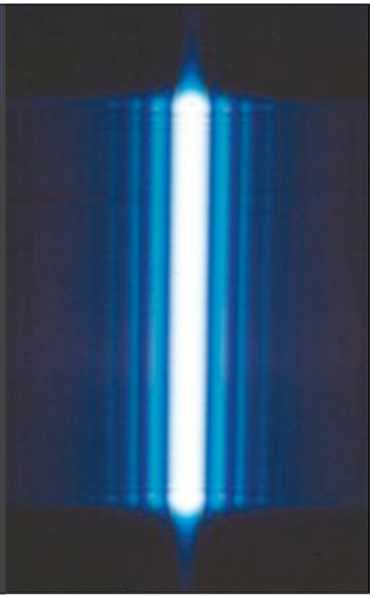
Fraunhofer Diffraction Pattern

- A **Fraunhofer diffraction pattern** occurs when the rays leave the diffracting object in parallel directions
  - Screen very far from the slit
  - Could be accomplished by a converging lens



Diffraction Pattern, Single Slit

- The diffraction pattern consists of the central maximum and a series of secondary maxima and minima
- The pattern is similar to an interference pattern

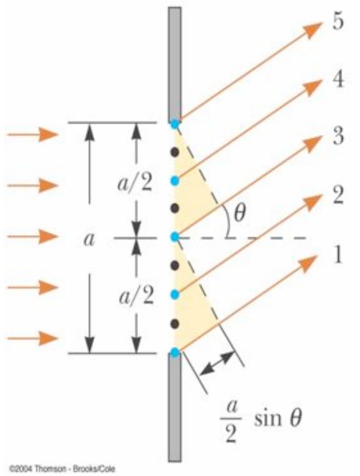


Diffraction vs. Diffraction Pattern

- *Diffraction* refers to the general behavior of waves spreading out as they pass through a slit
- A *diffraction pattern* is actually a misnomer that is deeply entrenched
  - The pattern seen on the screen is actually another *interference* pattern
  - The interference is between parts of the incident light illuminating different regions of the slit

Single-Slit Diffraction

- According to Huygens's principle, each portion of the slit acts as a source of light waves
- Therefore, light from one portion of the slit can interfere with light from another portion
- Wave 1 travels farther than wave 3 by an amount equal to the path difference
  - (a/2) sin θ
- If this path difference is exactly half of a wavelength, the two waves cancel each other and destructive interference results
- In general, *destructive interference* occurs for a single slit of width *a* when
- $\sin \theta_{\text{dark}} = m \lambda / a$
  - $m = \pm 1, \pm 2, \pm 3, \ldots$



Quiz 1

A single slit of width W has light of a certain wavelength incident.

If the width W is decreased, which of the following is true?

- The diffraction pattern of the slit on a screen will get narrower.
- → The diffraction pattern of the slit on a screen will get broader.

Diffraction Summary

Condition for halves of slit to destructively interfere $\sin(\theta) = \frac{\lambda}{D}$

Condition for quarters of slit to destructively interfere $\sin(\theta) = 2\frac{\lambda}{D}$

Condition for sixths of slit to destructively interfere $\sin(\theta) = 3\frac{\lambda}{D}$

$D\sin\theta = m\lambda$ (m=1, 2, 3, …)

THIS FORMULA LOCATES MINIMA!!

Narrower slit => broader pattern

Quiz 2

A laser is shone through a very small hole onto a screen.

If the diameter of the hole were decreased, the laser spot on the screen would...

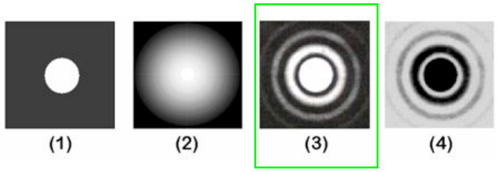
- get bigger.
- → get smaller.

Quiz

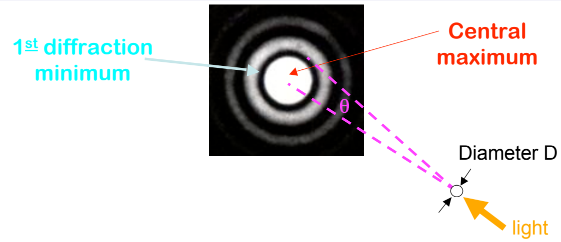
A laser is shone through a very small hole onto a screen.

Which drawing correctly depicts the pattern of light on the screen?

- 1
- 2
- 3
- 4



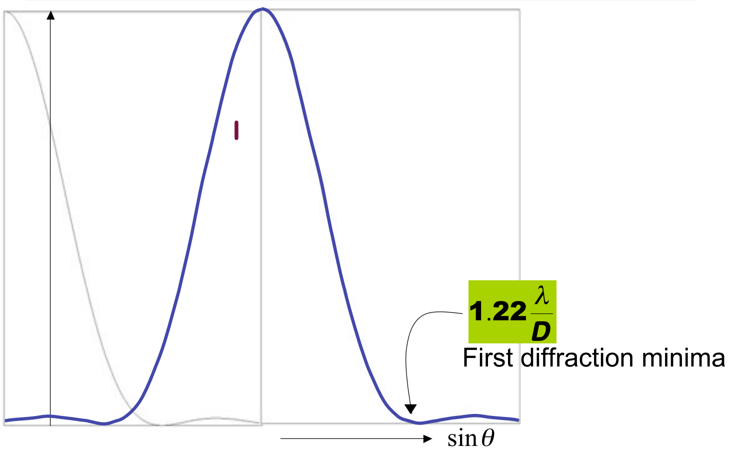
Diffraction from Circular Aperture

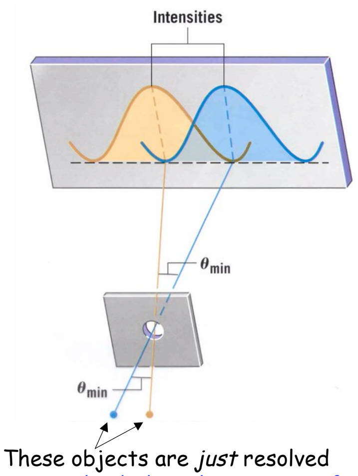


Maxima and minima will be a series of bright and dark rings on screen

First diffraction minimum is at $\sin\theta = 1.22\frac{\lambda}{D}$

Intensity from Circular Aperture





Two objects are just resolved when the maximum from one is at the minimum of the other.

Quiz

Astronaut Joe is standing on a distant planet with binary suns. He wants to see them but knows it's dangerous to look straight at them. So he decides to build a pinhole camera by poking a hole in a card. Light from both suns shines through the hole onto a second card. But when the camera is built, Astronaut Joe can only see one spot on the second card!

To see the two suns clearly, should he make the pinhole larger or smaller?

→ – Larger
– Smaller

Resolving Power Question

$$\sin\theta_{min} \approx \theta_{min} = 1.22\frac{\lambda}{D}$$

How does the maximum resolving power of your eye change when the brightness of the room is decreased.

1) Increases 2) Constant 3) Decreases

When the light is low, your pupil dilates (D can increase by factor of 10!)

Recap

- Huygens' Principle: Each point on wave front acts as coherent source and can interfere.
- Interference: Coherent waves
  - Full wavelength difference = Constructive
  - ½ wavelength difference = Destructive
- Multiple Slits (2 or more slits with separation d)
  - Constructive $d \sin(\theta) = m \lambda$ (m=1,2,3…)
  - More slits = brighter max, darker mins
- Single Slit:
  - Destructive: $D \sin(\theta) = m \lambda$ (m=1,2,3…)
  - Resolution: Max from 1 at Min from 2