PHY 1214
General Physics II

Lecture 29
Wave Optics / Interference of Light
July 25, 2005

Weldon J. Wilson
Professor of Physics and Engineering
Howell Hall 221H
wwilson@ucok.edu

Lecture Schedule (Weeks 7-8)

WEEK #7
- M July 18 - Reflection and Spherical Mirrors (25.4-25.7) / Refraction of Light (26.1-26.5)
- T July 19 - Lenses (26.6-26.9) / Optical Instruments (26.10-26.15)
- W July 20 - Optical Instruments (26.10-26.15) / Interference of Light (27.1-27.2)
- R July 21 - Diffraction (27.5) / The Diffraction Grating (27.7)

WEEK #8
- M July 25 - Special Relativity (28.1-28.4) / Relativistic Momentum and Energy (28.5-28.6)
- T July 26 - Photons (29.1-29.4)/ The Wave Nature of Matter (29.5-29.7)
- W July 27 - Nuclear Structure (31.1-31.3)
- R July 28 - Nuclear Radiation (31.4-31.8)

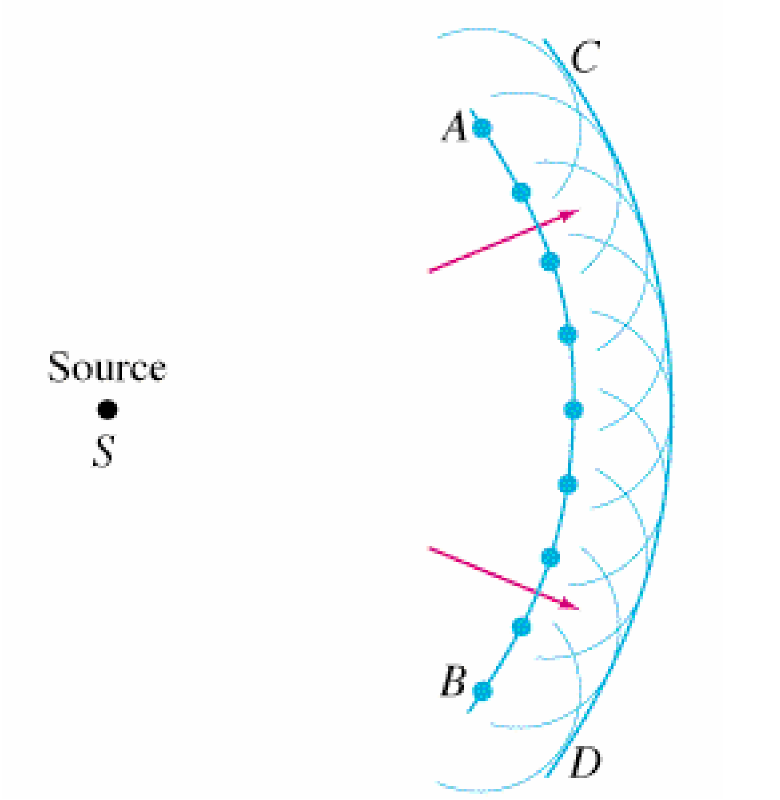
WEEK #9
- **M August 1 - FINAL EXAM, 10:30-12:30 in Howell Hall 101**
  PART 1: CHAPTERS 24, 25, 26, 27, 28, 29, 31, 32)
  PART 2: CHAPTERS 18, 19, 20, 21, 22)

We are here

Wave Nature of Light

- Back in the 1600s, Huygens developed an approach that is very helpful
- "*Every point on a wave front can be considered as a source of tiny wavelets that spread out in the forward direction at the speed of the wave itself. The new wave front is the envelope of all the wavelets - the tangent to all of them.*

Wave Nature of Light

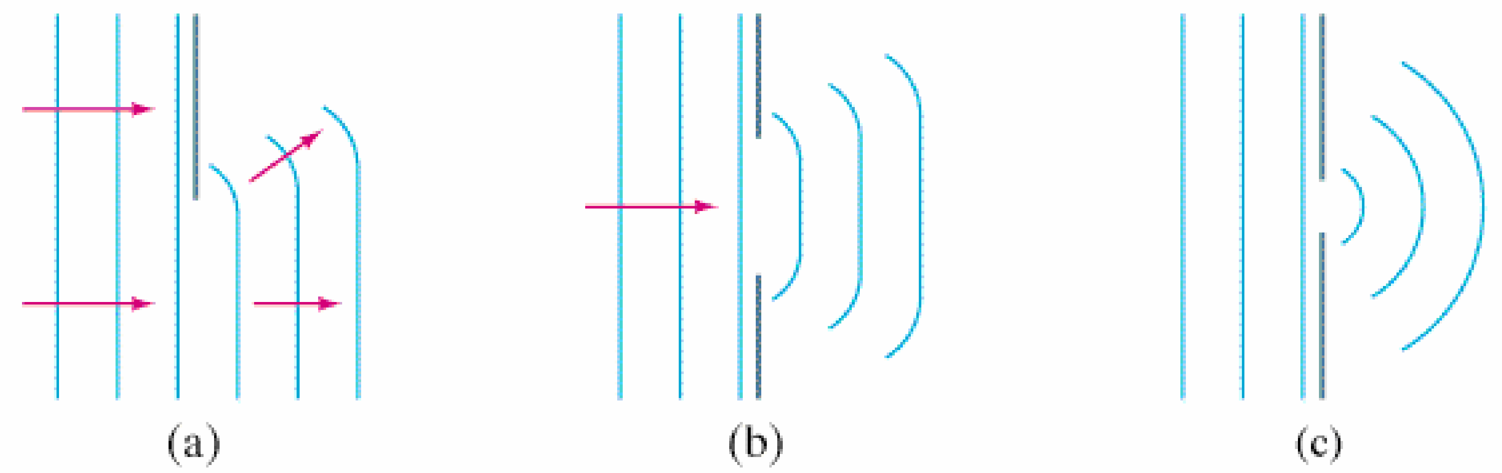


Huygen's Principle shows how the wave front moves from position AB to position CD.

We just create a lot of new little sources and let each one generate a new wave. The combination forms a new wave front!

Wave Nature of Light

- See how the wavelets at the edges let the light bend around corners!!!
- As the slit gets smaller, the bending is more obvious.

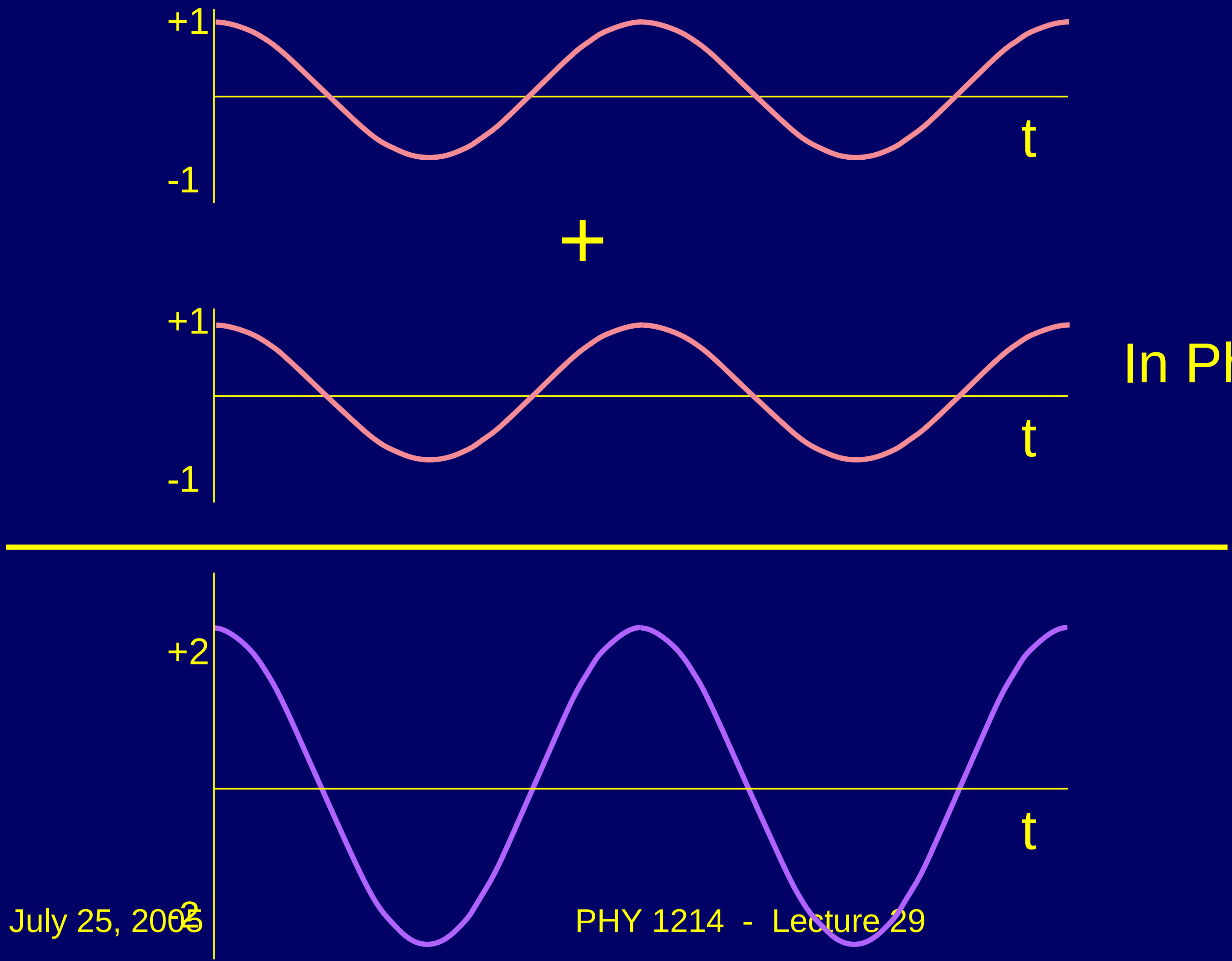


Interference

- Light waves interfere with each other much like mechanical waves do
- All interference associated with light waves arises when the electromagnetic fields that constitute the individual waves combine
- LINEAR SUPERPOSITION!

Superposition

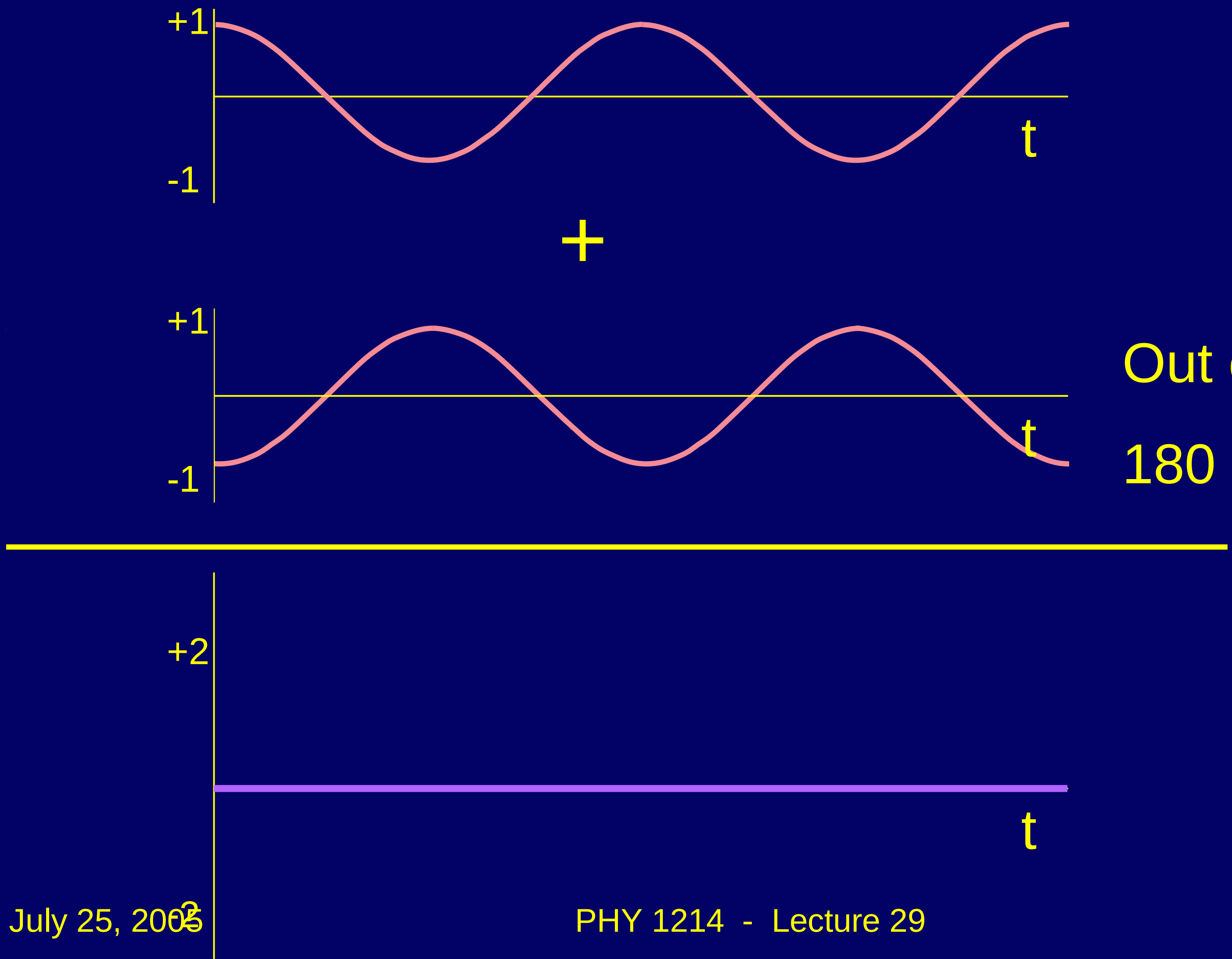
Constructive Interference



In Phase

Superposition

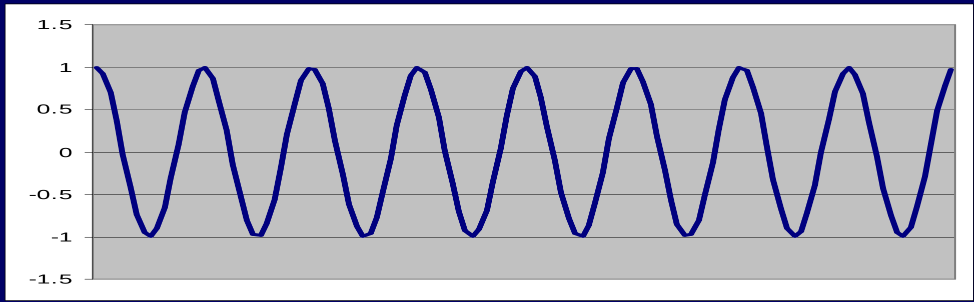
Destructive Interference



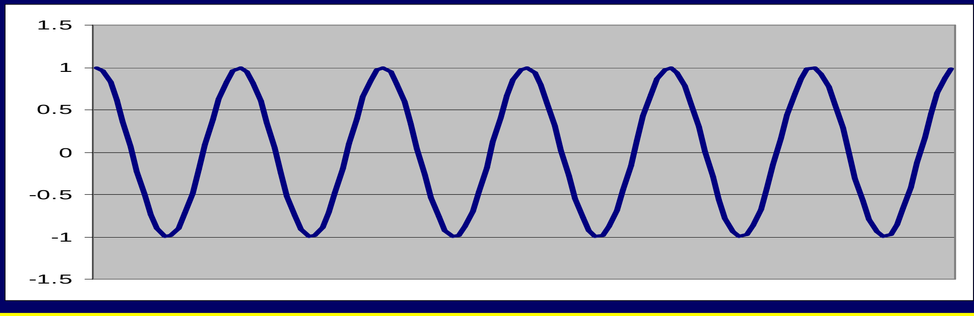
Out of Phase

180 degrees

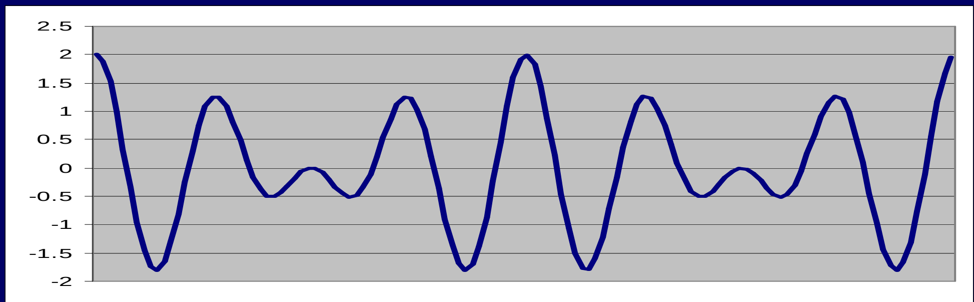
Superposition



+



Different f



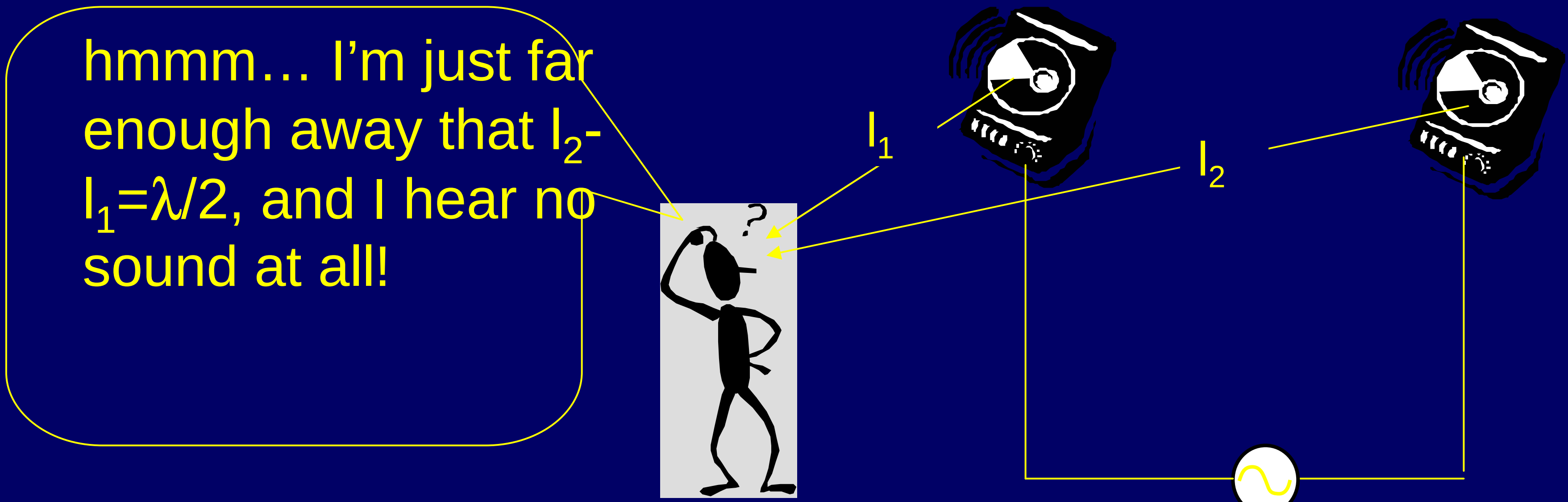
1) Constructive 2) Destructive 3) Neither

Interference Requirements

- Need two (or more) waves
- Must have same frequency
- Must be coherent (i.e. waves must have definite phase relation)

Interference for Sound …

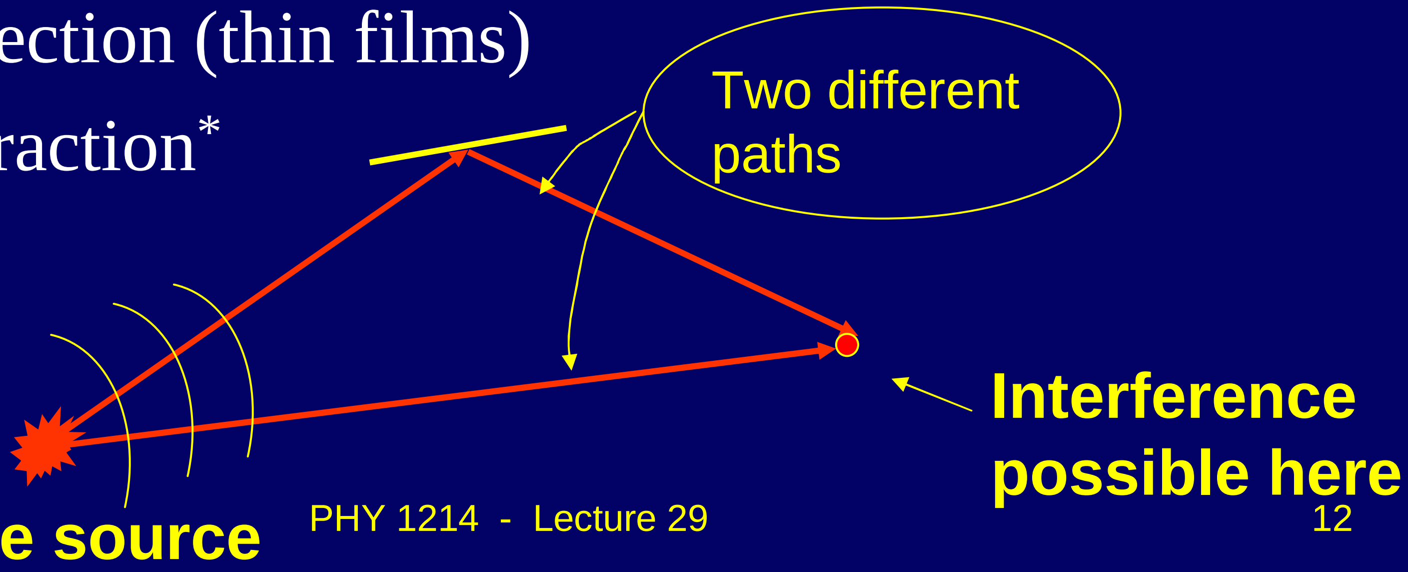
For example, a pair of speakers, driven in phase, producing a tone of a single f and λ:



But this won't work for light--can't get coherent sources

Interference for Light …

- Can't produce coherent light from separate sources. (f ≈ 10^{14} Hz)
- Need two waves from <u>single source</u> taking <u>two different paths</u>
  - Two slits
  - Reflection (thin films)
  - Diffraction*



Conditions for Interference

- For sustained interference between two sources of light to be observed, there are two conditions which must be met
  - The sources must be *coherent*
    - They must maintain a constant phase with respect to each other
  - The waves must have identical wavelengths

Producing Coherent Sources

- Light from a monochromatic source is allowed to pass through a narrow slit
- The light from the single slit is allowed to fall on a screen containing two narrow slits
- The first slit is needed to insure the light comes from a tiny region of the source which is coherent
- Old method

Producing Coherent Sources, cont.

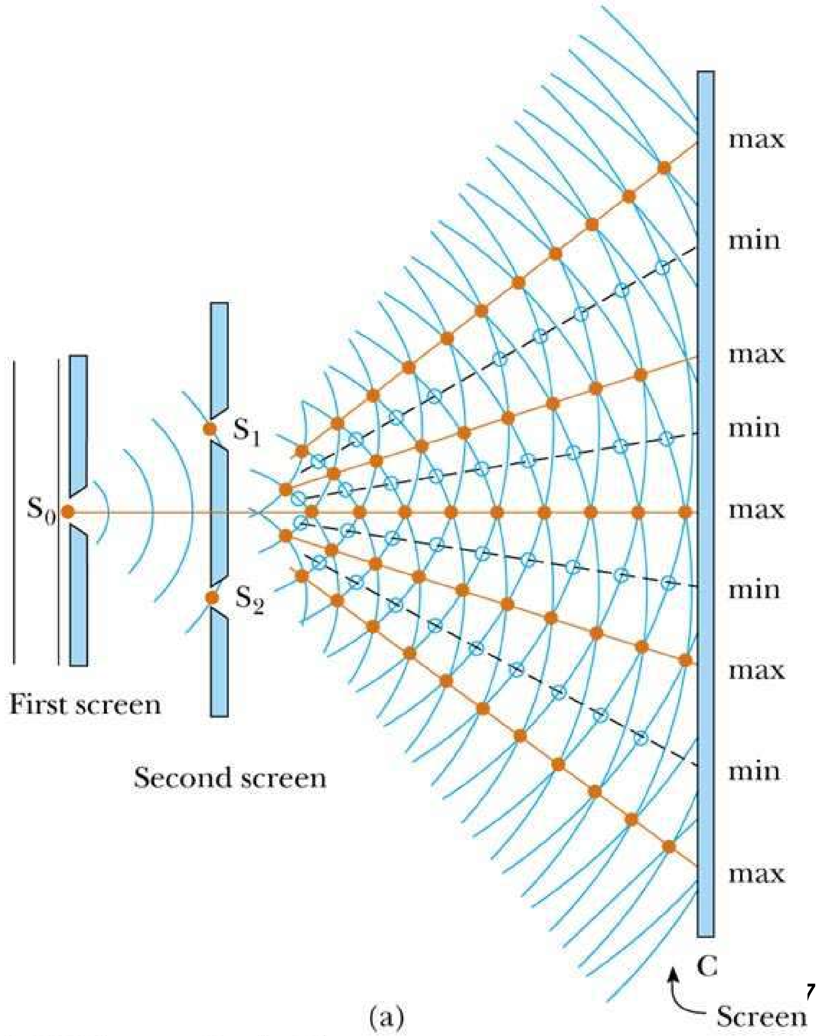
- Currently, it is much more common to use a laser as a coherent source
- The laser produces an intense, coherent, monochromatic parallel beam over a width of several millimeters

Young's Double Slit Experiment

- Thomas Young first demonstrated interference in light waves from two sources in 1801
- Light is incident on a screen with a narrow slit, S_o
- The light waves emerging from this slit arrive at a second screen that contains two narrow, parallel slits, S_1 and S_2

Young's Double Slit Experiment, Diagram

- 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

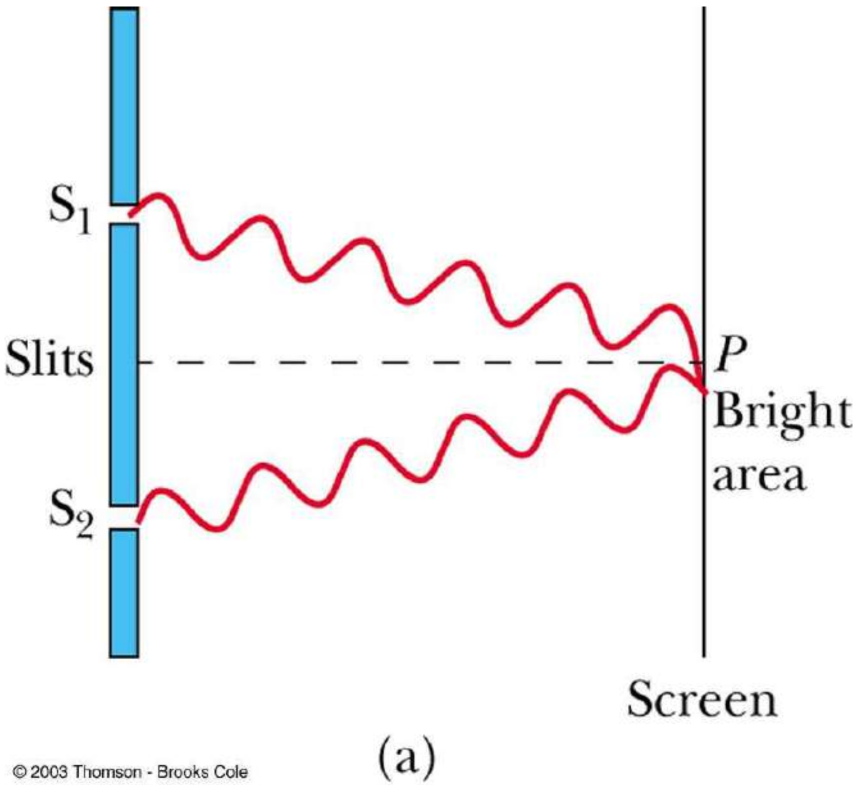


Resulting Interference Pattern

- The light from the two slits form 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

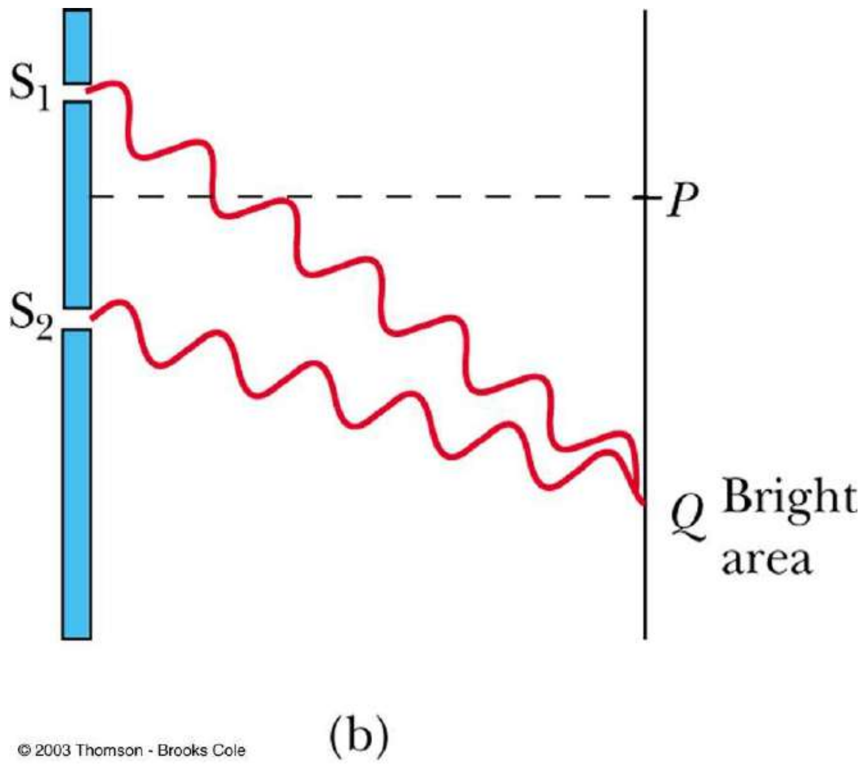
Interference Patterns

- Constructive interference occurs at the center point
- The two waves travel the same distance
  - Therefore, they arrive in phase



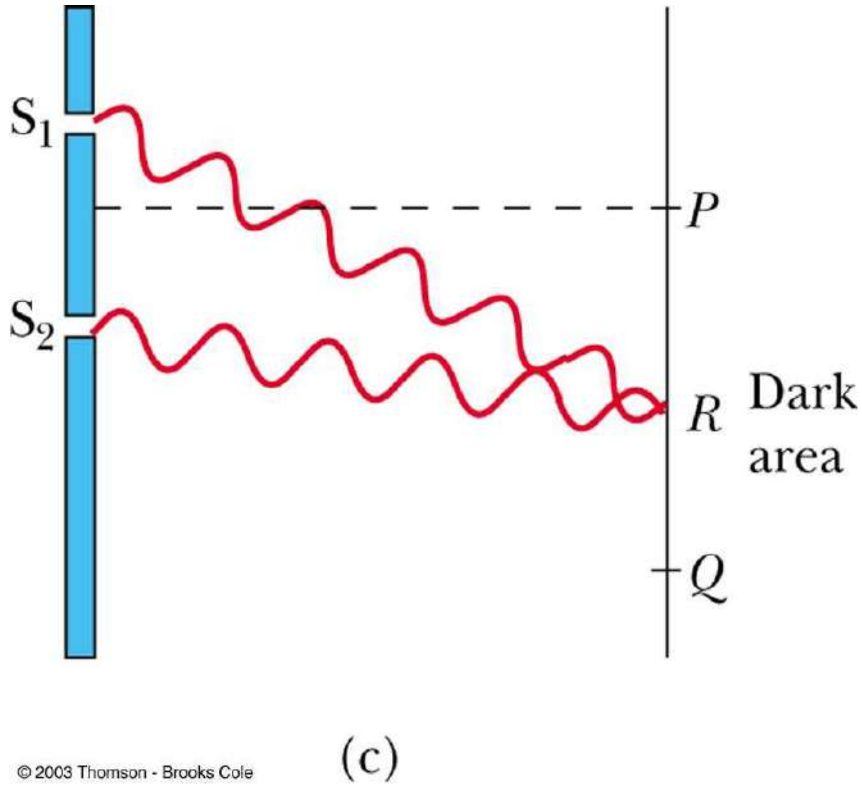
Interference Patterns, 2

- The upper wave has to travel farther than the lower wave
- The upper wave travels one wavelength farther
  - Therefore, the waves arrive in phase
- A bright fringe occurs



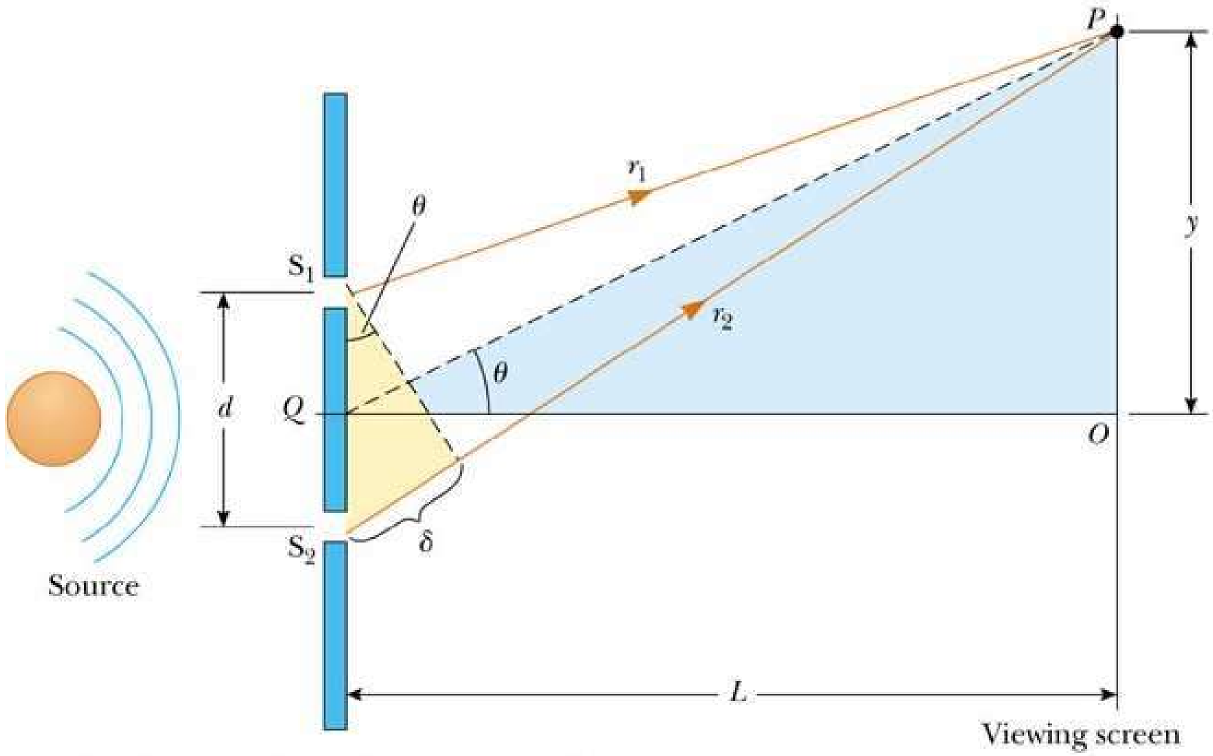
Interference Patterns, 3

- The upper wave travels one-half of a wavelength farther than the lower wave
- The trough of the bottom wave overlaps the crest of the upper wave (180° phase shift)
- This is destructive interference
  - A dark fringe occurs

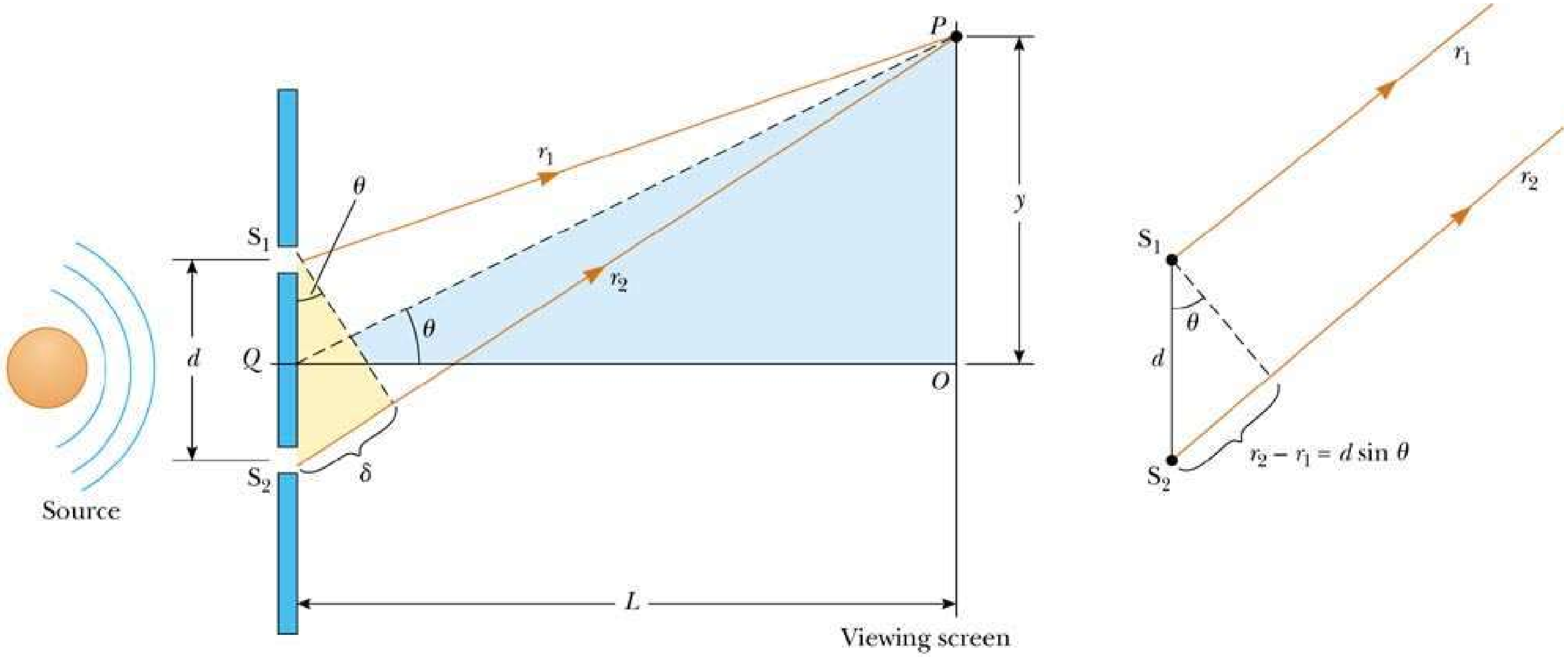


Interference Equations

- The path difference, δ, is found from the tan triangle
- $\delta = r_2 - r_1 = d \sin \theta$



Interference Equations, 2



(a) (b)

- This assumes the paths are parallel
- Not exactly, but a very good approximation ($L >> d$)

Interference Equations, 3

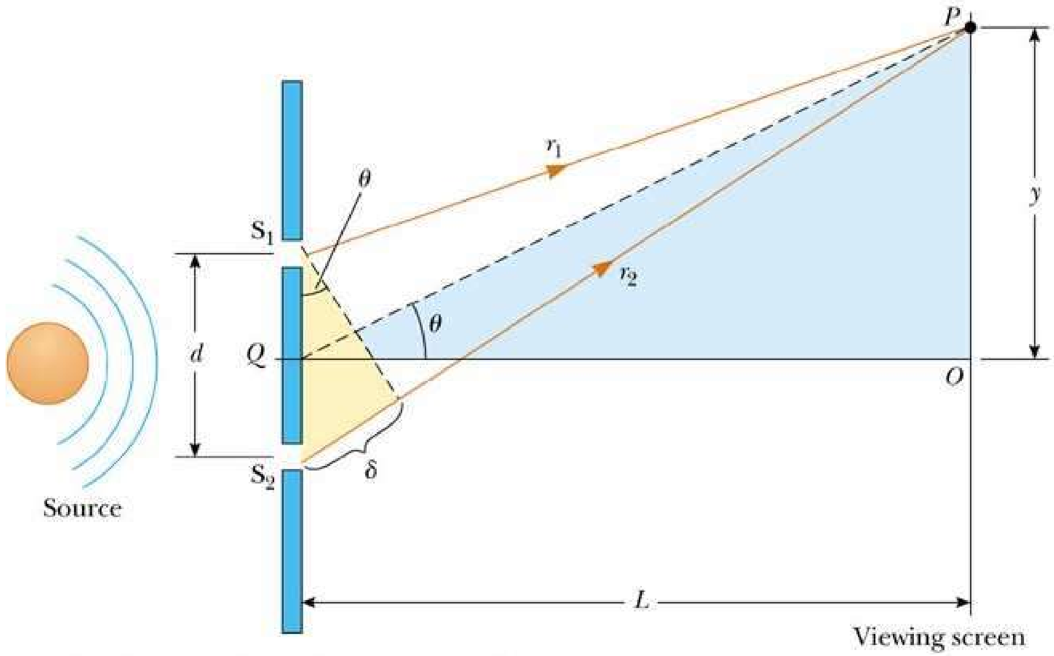
- For a bright fringe, produced by constructive interference, the path difference must be either zero or some integral multiple of of the wavelength
- $\delta = d \sin \theta_{bright} = m \lambda$
  - $m = 0, \pm 1, \pm 2, \ldots$
  - *m* is called the *order number*
    - When $m = 0$, it is the zeroth order maximum
    - When $m = \pm 1$, it is called the first order maximum

Interference Equations, 4

- When destructive interference occurs, a dark fringe is observed
- This needs a path difference of an odd half wavelength
- $\delta = d \sin \theta_{dark} = (m + ½) \lambda$
  - $m = 0, \pm 1, \pm 2, \ldots$

Interference Equations, 5

- The positions of the fringes can be measured vertically from the zeroth order maximum
- $y = L \tan \theta \approx L \sin \theta$
- Assumptions
  - $L >> d$
  - $d >> \lambda$
  - $\tan \theta \approx \sin \theta$



θ is small and therefore the approximation $\tan \theta \approx \sin \theta$ can be used

Interference Equations, final

- For bright fringes (use $\sin\theta_{\text{bright}} = m\lambda/d$)

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

- For dark fringes (use $\sin\theta_{\text{dark}} = \lambda(m + \frac{1}{2})/d$)

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

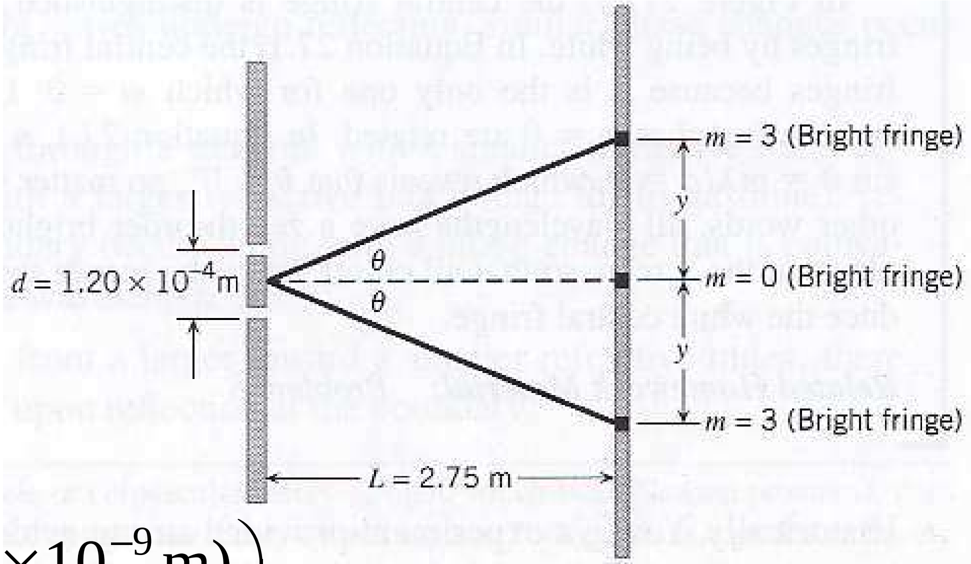
Uses for Young's Double Slit Experiment

- 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 is inconceivable that particles of light could cancel each other

Example:

Red light (λ=664 nm) is used in Young's experiment according to the drawing. Find the distance *y* on the screen between the central bright and the third-order bright fringe.

Solution:



$$d\sin\theta = m\lambda$$

$$\Rightarrow \quad \theta = \sin^{-1}\left(\frac{m\lambda}{d}\right)$$

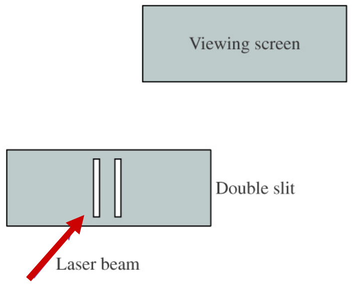
$$d\sin\theta = m\lambda \rightarrow \theta = \sin^{-1}\left(\frac{3(664\times10^{-9}\ \text{m})}{1.20\times10^{-4}\ \text{m}}\right) = 0.95^\circ$$

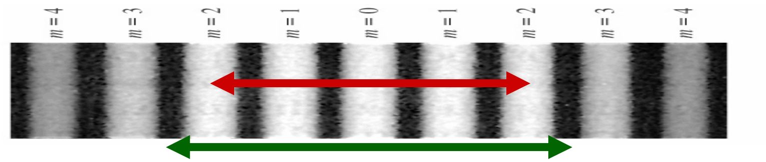
$$y = L\tan\theta = (2.75\ \text{m})(\tan 0.95^\circ) = 0.046\ \text{m}$$

Example: Double Slit Interference of a Laser Beam

Light from a helium-neon laser (λ = 633 nm) illuminates two slits placed 0.40 mm apart. A viewing screen is placed 2.0 m behind the slits.

What are the distances Δy_2 between the two m=2 bright fringes and $\Delta y'_2$ between the two m=2 dark fringes?





$$y_2 = 2\frac{\lambda L}{d} = 2\frac{(6.33\times10^{-7}\text{ m})(2.0\text{ m})}{(4.0\times10^{-4}\text{ m})} = 6.33\times10^{-3}\text{ m}$$

$$\Delta y_2 = 2y_2 = 12.7\times10^{-3}\text{ m} = 12.7\text{ mm}$$

$$y'_2 = (2+\tfrac{1}{2})\frac{\lambda L}{d} = \frac{5}{2}\frac{(6.33\times10^{-7}\text{ m})(2.0\text{ m})}{(4.0\times10^{-4}\text{ m})} = 7.9\times10^{-3}\text{ m}$$

$$\Delta y'_2 = 2y'_2 = 15.8\times10^{-3}\text{ m} = 15.8\text{ mm}$$

Example: Measuring Wavelength of Light

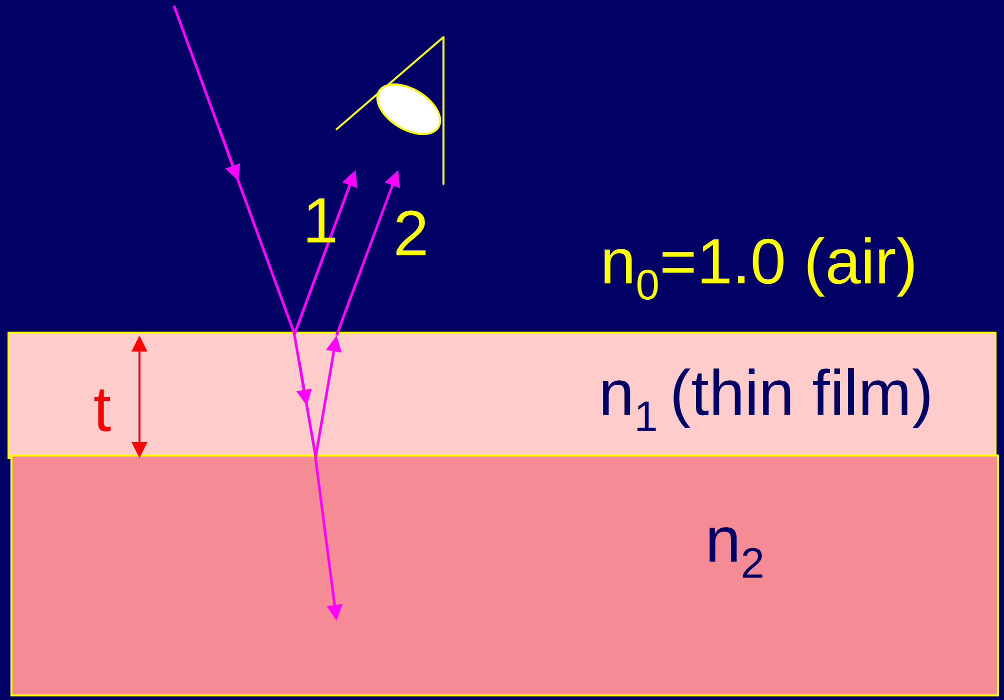
A screen is placed 1.0 m behind a pair of slits, which are spaced 0.30 mm apart. When this system is illuminated by a certain frequency of monochromatic light, ten bright fringes are found to span a distance of 1.65 cm on the screen.

What is the wavelength of the light?

$$\Delta y = 9\frac{\lambda L}{d}$$

$$\lambda = \frac{d\Delta y}{9L} = \frac{(3.0\times 10^{-4}\ \text{m})(1.65\times 10^{-2}\ \text{m})}{9(1.0\ \text{m})} = 5.50\times 10^{-7}\ \text{m} = 550\ \text{nm}$$

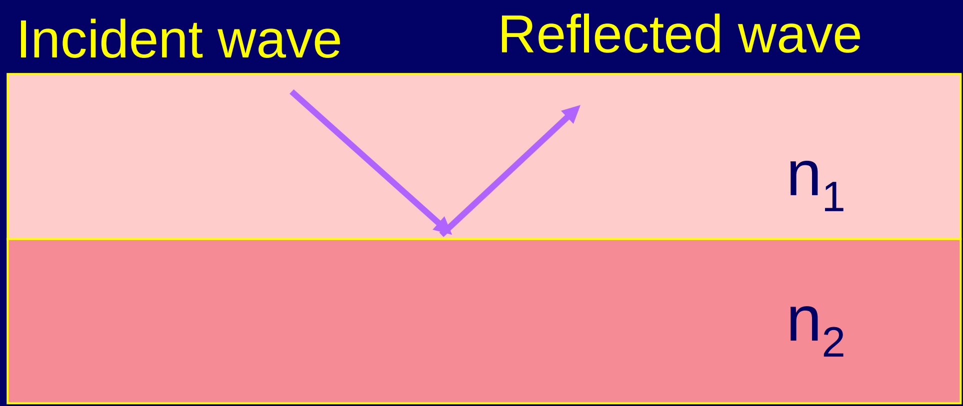
Thin Film Interference



Get two waves by reflection off of two different interfaces.

Ray 2 travels approximately 2t further than ray 1.

Reflection + Phase Shifts

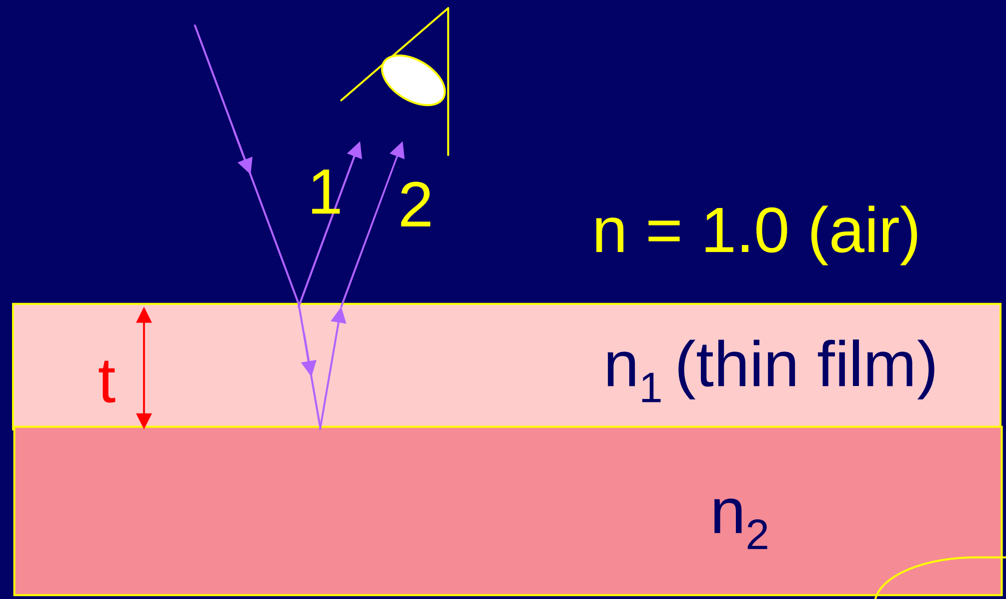


Upon reflection from a boundary between two transparent materials, the phase of the reflected light *may* change.

- If $n_1 > n_2$ - no phase change upon reflection.
- If $n_1 < n_2$ - phase change of 180º upon reflection.
  (equivalent to the wave shifting by $\lambda/2$.)

Thin Film Summary

Determine δ, number of extra wavelengths for each ray.



This is important!

Reflection: Ray 1: $\delta_1 = 0$ or ½ + Distance: 0

Ray 2: $\delta_2 = 0$ or ½ + $2\,t/\lambda_{film}$

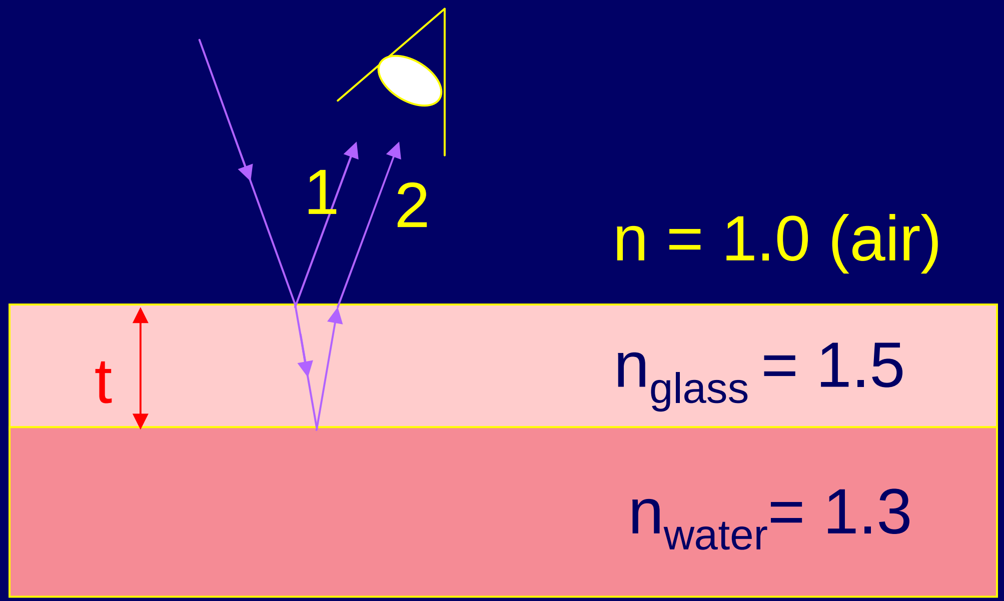
Note: this is wavelength in film! ($\lambda_{film} = \lambda_o/n_1$)

If $|(\delta_2 - \delta_1)| = 0, 1, 2, 3 \ldots$ (m) constructive

If $|(\delta_2 - \delta_1)| =$ ½ , 1 ½, 2 ½ …. (m + ½) destructive

Example

Thin Film Practice



Blue light (λ_o = 500 nm) incident on a glass (n_{glass} = 1.5) cover slip (t = 167 nm) floating on top of water (n_{water} = 1.3).

Is the interference constructive or destructive or neither?

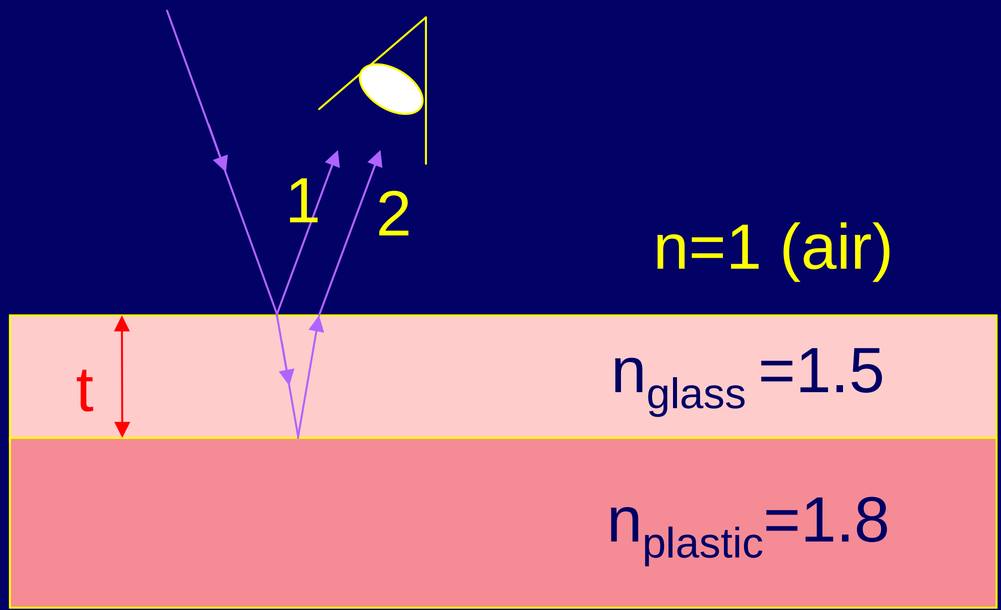
$\delta_1 = ½$ Reflection at air-film interface only

$\delta_2 = 0 + 2t / \lambda_{glass} = 2t\, n_{glass} / \lambda_0 = 1$

Phase shift = $\delta_2 - \delta_1$ = ½ wavelength

Thin Film

Blue light λ = 500 nm incident on a thin film (t = 167 nm) of glass on top of plastic. The interference is:



(1) constructive

(2) destructive

(3) neither

$\delta_1 = ½$ Reflection at both interfaces!

$\delta_2 = ½ + 2t / \lambda_{glass} = ½ + 2t\, n_{glass} / \lambda_0 = ½ + 1$

Phase shift = $\delta_2 - \delta_1$ = 1 wavelength

End of Lecture 29

- Before the next lecture, Read *Sections* 27.1 through 27.4