Thin Film Interference
Later
Iridescence
Diffraction & Interference
Geometric RAY Optics (Ch 35)

\[ \theta_i = \theta_r \]

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]
Ray Optics: Ignores Diffraction and Interference of waves!

Diffraction depends on SLIT WIDTH: the smaller the width, relative to wavelength, the more bending and diffraction.

Ray Optics assumes that $\lambda \ll d$, where $d$ is the diameter of the opening.
This approximation is good for the study of mirrors, lenses, prisms, etc.

Wave Optics assumes that $\lambda \sim d$, where $d$ is the diameter of the opening.
This approximation is good for the study of interference.
James Clerk Maxwell
1860s

Light is wave.

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3.0 \times 10^8 \text{ m/s} \]

Speed of Light in a vacuum:
186,000 miles per second
300,000 kilometers per second
3 \times 10^8 \text{ m/s}
The Electromagnetic Spectrum
Hydrogen Spectra
Incandescent Light Bulb
Full Spectrum of Light
All frequencies excited!
Visible Light

- Different wavelengths correspond to different colors.
- The range is from red ($\lambda \sim 7 \times 10^{-7}$ m) to violet ($\lambda \sim 4 \times 10^{-7}$ m).
Double Slit is VERY IMPORTANT because it is evidence of waves. Only waves interfere like this.
If light were made of hard bullets, there would be no interference pattern.
In reality, light does show an interference pattern.
Light acts like a wave going through the slits but arrive at the detector like a particle.
Particle Wave Duality
Double Slit for Electrons shows Wave Interference! Key to Quantum Theory!
Interference pattern builds one electron at a time.

Electrons act like waves going through the slits but arrive at the detector like a particle.

\[ \lambda_e = 2.4 \times 10^{-11} \text{m} \]
Limits of Vision

Electron Waves

\[ \lambda_e = 2.4 \times 10^{-11} m \]
Electron Diffraction with Crystals (Chapter 38)

Incident beam → Electron gun → Electron detector → Scattered electron beam

Metal target (crystalline Nickel)

decagonal Al-Co-Ni

basic Co

by S. Ritsch and C. Beeli

1-dim QC

5-fold

HT 5-fold

Type I superstructure
The resolving power of an optical lens depends on the wavelength of the light used. An electron-microscope exploits the wave-like properties of particles to reveal details that would be impossible to see with visible light.
Intereference of 2-D Coherent Sound Waves

Phase Difference at P: \( \Delta \phi = \frac{2\pi}{\lambda} \Delta r, \quad \Delta \phi_0 = 0 \)
Interference of 2-D Coherent Light Waves

1. A plane wave is incident on the double slit.

2. Waves spread out behind each slit.

3. The waves interfere in the region where they overlap.

4. Bright fringes occur where the antinodal lines intersect the viewing screen.
Diffraction depends on SLIT WIDTH: the smaller the width, relative to wavelength, the more bending and diffraction.
Single Slit Interference Is called Diffraction (Chapter 38)
Single Slit

(a)

(b)
These single slit diffraction patterns were photographed with a helium-neon laser as the light source and a micrometer-controlled single slit. The sketches of the slit widths at right were scaled to the difference between the first minima of the diffraction patterns. If the geometry is such that the small angle approximation is valid, the width of the pattern is inversely proportional to the slit width.
Young’s Double Slit

• 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
Interference of 2-D Coherent Light Waves
Double Slit Interference
Dependence on Slit Separation

KEY:

Slit Width = 48
Wavelength = 16

Crests
Troughs
Derive Fringe Equations

“m” is the fringe order.

• Maxima: bright fringes

\[ d \sin \theta = m \lambda \]

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

• Minima: dark fringes

\[ d \sin \theta = \left( m + \frac{1}{2} \right) \lambda \]

\[ y_{\text{dark}} = \frac{\lambda L}{d} \left( m + \frac{1}{2} \right) \quad (m = 0, \pm 1, \pm 2 \ldots) \]
Phase Difference at P: \( \Delta \phi = \frac{2\pi}{\lambda} \Delta r \)

Constructive interference occurs at point \( O \) when the waves combine.

Constructive interference also occurs at point \( P \).

Destructive interference occurs at point \( R \) when the two waves combine because the lower wave falls one-half a wavelength behind the upper wave.

Constructive: \( \Delta \phi = 2m\pi, \quad \Delta r = m\lambda, \quad m = 0, 1, 2, 3... \)

Destructive: \( \Delta \phi = (2m + 1)\pi, \quad \Delta r = (m + \frac{1}{2}), \quad m = 0, 1, 2, 3... \)
Phase Difference at P: \( \Delta \phi = \frac{2\pi}{\lambda} \Delta r \)

Constructive: \( \Delta \phi = 2m\pi, \quad \Delta r = m\lambda, \quad m = 0, 1, 2, 3... \)

Destructive: \( \Delta \phi = (2m + 1)\pi, \quad \Delta r = (m + \frac{1}{2}), \quad m = 0, 1, 2, 3... \)
Derive Fringe Equations

“m” is the fringe order.

- **Maxima: bright fringes**
  \[ d \sin \theta = m \lambda \]
  \[ y_{\text{bright}} = \frac{\lambda L}{d} m \quad (m = 0, \pm 1, \pm 2 \ldots) \]

- **Minima: dark fringes**
  \[ d \sin \theta = \left( m + \frac{1}{2} \right) \lambda \]
  \[ y_{\text{dark}} = \frac{\lambda L}{d} \left( m + \frac{1}{2} \right) \quad (m = 0, \pm 1, \pm 2 \ldots) \]
Problem

Red light ($\lambda=664\text{nm}$) is used in Young’s double slit as shown. Find the distance $y$ on the screen between the central bright fringe and the third order bright fringe.

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

![Diagram showing Young's double slit experiment with distance $d = 1.20 \times 10^{-4} \text{ m}$ and screen distance $L = 2.75 \text{ m}$]
Measuring the wavelength of light

\[ \Delta y = \frac{\lambda L}{d} \] Fringe Spacing.

A double-slit interference pattern is observed on a screen 1.0 m behind two slits spaced 0.30 mm apart. 9 bright fringes span a distance of 1.7 cm. What is the wavelength of light?
EXAMPLE 22.2  Measuring the wavelength of light

SOLVE  The fringe spacing is

\[ \Delta y = \frac{1.7 \text{ cm}}{9} = 1.89 \times 10^{-3} \text{ m} \]

Using this fringe spacing in Equation 22.7, we find that the wavelength is

\[ \lambda = \frac{d}{L} \Delta y = 5.7 \times 10^{-7} \text{ m} = 570 \text{ nm} \]

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

A Young’s interference experiment is performed with monochromatic light. The separation between the slits is 0.500 mm, and the interference pattern on a screen 3.30 m away shows the first side maximum 3.40 mm from the center of the pattern. What is the wavelength?
Double Slit

The image shows the light intensity on a screen behind a double slit. The slit spacing is 0.20 mm and the wavelength of light is 600 nm. What is the distance from the slits to the screen?

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

Intensity (mW/m²)

0 12

2.0 cm
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 $\lambda$.
B. 1.5 $\lambda$.
C. 2.0 $\lambda$.
D. 2.5 $\lambda$.
E. 3.0 $\lambda$. 

Central maximum
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.
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.
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.
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

\[ \Delta y = \frac{\lambda}{d} \]

and green light has a shorter wavelength.

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.

Central maximum
Intensity

The intensity of a wave, the power per unit area, is the rate at which energy is being transported by the wave through a unit area $A$ perpendicular to the direction of travel of the wave:

$$I = \frac{\varphi}{\text{Area}} \left[ \frac{\text{W}}{\text{m}^2} \right]$$

Power Transmitted on a String:

$$\varphi = \frac{1}{2} \mu \omega^2 A^2 v$$

Power Transmitted by Sound:

$$\varphi = \frac{1}{2} \rho A \omega^2 s_{\text{max}}^2 v$$

Intensity $\sim (\text{Amplitude})^2$
Chapter 18: Wave Interference

\[ y_1 + y_2 = 2A \cos \left( \frac{\Delta \phi}{2} \right) \sin(kx - \omega t + \frac{\Delta \phi}{2}) \]

Resultant Amplitude: \( 2A \cos \left( \frac{\Delta \phi}{2} \right) \)

Constructive Interference: \( \Delta \phi = 2n\pi, \quad n = 0,1,2,3... \)

Destructive Interference: \( \Delta \phi = (2n + 1)\pi, \quad n = 0,1,2,3... \)
Constructive or Destructive?
(Identical in phase sources)

Phase Difference at P: \( \Delta \phi = \frac{2\pi}{\lambda} \Delta r + \phi_0 \)

\[\Delta \phi = \frac{2\pi}{\lambda} (1\lambda) = 2\pi\]

Constructive!

Resultant Amplitude: \( 2A \cos \left( \frac{\Delta \phi}{2} \right) \)

Constructive Interference: \( \Delta r = n\lambda, \quad \Delta \phi = 2n\pi, \quad n = 0, 1, 2, 3... \)

Destructive Interference: \( \Delta r = (2n + 1)\frac{\lambda}{2}, \quad \Delta \phi = (2n + 1)\pi, \quad n = 0, 1, 2, 3... \)
Intensity of Light Waves

\[ E = E_{\text{max}} \cos (kx - \omega t) \]
\[ B = B_{\text{max}} \cos (kx - \omega t) \]

\[ \frac{E_{\text{max}}}{B_{\text{max}}} = \frac{\omega}{k} = \frac{E}{B} = c \]

\[ I = S_{\text{av}} = \frac{E_{\text{max}}B_{\text{max}}}{2\mu_0} = \frac{E_{\text{max}}^2}{2\mu_0 c} = \frac{cB_{\text{max}}^2}{2\mu_0} \]

\[ I \propto E_{\text{max}}^2 \]
Intensity Distribution
Resultant Field

• The magnitude of the resultant electric field comes from the superposition principle
  \[ E_P = E_1 + E_2 = E_0 \sin \omega t + \sin (\omega t + \phi) \]

• This can also be expressed as
  \[ E_P = 2E_o \cos \left( \frac{\phi}{2} \right) \sin \left( \omega t + \frac{\phi}{2} \right) \]
  - \( E_P \) has the same frequency as the light at the slits
  - The amplitude at P is given by \( 2E_o \cos (\phi / 2) \)

• Intensity is proportional to the square of the amplitude:
  \[ I \propto A^2 \]
  \[ I = I_{\text{max}} \cos^2(\Delta\phi / 2) \]
Light Intensity

\[ I \propto A^2 \]

- The interference pattern consists of equally spaced fringes of equal intensity

- This result is valid only if \( L >> d \) and for small values of \( \theta \)

\[ I = I_{\text{max}} \cos^2 \left( \frac{\Delta \phi}{2} \right) \]

\[
\Delta \phi = \frac{2\pi}{\lambda} \Delta r
\]

\[
I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \approx I_{\text{max}} \cos^2 \left( \frac{\pi d}{\lambda L} y \right)
\]
Intensity

In a double-slit experiment, the distance between the slits is 0.2 mm, and the distance to the screen is 150 cm. What wavelength (in nm) is needed to have the intensity at a point 1 mm from the central maximum on the screen be 80% of the maximum intensity?

a. 900
b. 700
c. 500
d. 300
e. 600

\[ I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \approx I_{\text{max}} \cos^2 \left( \frac{\pi d}{\lambda L} y \right) \]
Double Slit Intensity

Two slits are illuminated with green light ($\lambda = 540$ nm). The slits are 0.05 mm apart and the distance to the screen is 1.5 m. At what distance (in mm) from the central maximum on the screen is the average intensity 50% of the intensity of the central maximum?

a. 1
b. 3
c. 2
d. 4
e. 0.4

\[
I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \approx I_{\text{max}} \cos^2 \left( \frac{\pi d}{\lambda L} \frac{y}{\lambda} \right)
\]
Double Slit Interference Reality
Combination of Single and Double
Double Slit Interference Reality
Combination of Single and Double

1. A plane wave is incident on the double slit.
2. Waves spread out behind each slit.
3. The waves interfere in the region where they overlap.
4. Bright fringes occur where the antinodal lines intersect the viewing screen.

In reality, the fringe intensity decreases because the intensity of the light from a single slit is not uniform.

Light intensity

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Intensity of Two-Slit Diffraction
Chapter 38

\[ I = I_{\text{max}} \cos^2 \left( \frac{\pi d \sin \theta}{\lambda} \right) \left[ \frac{\sin(\pi a \sin \theta / \lambda)}{\pi a \sin \theta / \lambda} \right]^2 \]

The diffraction pattern acts as an “envelope” (the blue dashed curve) that controls the intensity of the regularly spaced interference maxima.
Under the Fraunhofer conditions, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit diffraction envelope. This assumes that all the slits are identical.
Under the **Fraunhofer conditions**, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit diffraction envelope. This assumes that all the slits are identical.
Three Slit Diffraction

Under the Fraunhofer conditions, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit diffraction envelope. This assumes that all the slits are identical.
Five Slit Diffraction

Under the Fraunhofer conditions, the light curve of a multiple slit arrangement will be the interference pattern multiplied by the single slit.
Multiple Slits: Diffraction Gratings

For N slits, the intensity of the primary maxima is $N^2$ times greater than that due to a single slit.

For any value of $N$, the decrease in intensity in maxima to the left and right of the central maximum, indicated by the blue dashed arcs, is due to diffraction patterns from the individual slits, which are discussed in Chapter 38.
Michelson Interferometer

The fringe pattern shifts by one-half fringe each time $M1$ is moved a distance $\lambda/4$

http://www.youtube.com/watch?v=ETLG5SLFMZ0
http://www.youtube.com/watch?v=Z8K3gcHQiqk&feature=related
James Clerk Maxwell
1860s

Light is wave. The medium is the Ether.

\[ c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3.0 \times 10^8 \, \text{m/s} \]
The Luminiferous Aether was imagined by physicists since Isaac Newton as the invisible "vapor" or "gas aether" filling the universe and hence as the carrier of heat and light.
Rotate arms to produce interference fringes and find different speeds of light caused by the Ether Wind, due to Galilean Relativity: light should travel slower against the Ether Wind. From that you can find the speed of the wind.
http://www.youtube.com/watch?v=XavCw_Y9b8&feature=related

http://www.youtube.com/watch?v=4KFMeKJySwA&feature=related
Michelson-Morely Experiment
1887

The speed of light is independent of the motion and is always c. The speed of the Ether wind is zero.

OR….

Lorentz Contraction

The apparatus shrinks by a factor:

$$\sqrt{1 - \frac{v^2}{c^2}}$$
Clocks slow down and rulers shrink in order to keep the speed of light the same for all observers!
Time is Relative!
Space is Relative!
Only the SPEED OF LIGHT is Absolute!
On the Electrodynamics of Moving Bodies
1905
LIGO in Richland, Washington

http://www.youtube.com/watch?v=RzZgFKolfQI&feature=related
LISA

http://www.youtube.com/watch?v=DrWwWcA_Hgw&feature=related
Eye See YOU!!