Chapter 24

Wave Optics
An upright object is located a distance from a convex mirror that is less than the mirror's focal length. The image formed by the mirror is

- (1) virtual, upright, and larger than the object
- (2) real, inverted and smaller than the object
- (3) virtual, upright and smaller than the object
- (4) real, inverted and larger than the object
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Summary of Chapter 23

Convex mirrors \( f < 0 \)
Convex lens \( f > 0 \)
\( q > 0 \) real image
\( |m| > 1 \) larger image
\( m > 0 \) upright image

Multiple lens instruments.

\[ m = m_1 m_2 \]

\[ \frac{1}{p} + \frac{1}{q} = \frac{1}{f} \]

\[ m = \frac{h}{h'} = -\frac{q}{p} \]

\[ f = R / 2 \]

\[ \frac{1}{f} = (n - 1) \left[ \frac{1}{R_1} - \frac{1}{R_2} \right] \]
Wave Optics

- The wave nature of light is needed to explain various phenomena
  - Interference
  - Diffraction
  - Polarization
- The particle nature of light was the basis for ray (geometric) optics

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Examples of interference

- Burn marks in food cooked in old microwaves (non-rotating)
- Iridescent colors in soap bubbles, abalone shells and peacock plumes.

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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
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 beam over a width of several millimeters
- The laser light can be used to illuminate multiple slits directly
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, $S_0$.
- The light waves emerging from this slit arrive at a second screen that contains two narrow, parallel slits, $S_1$ and $S_2$. 

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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

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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 appears
- Destructive interference results in a dark fringe
Fringe Pattern

- The fringe pattern formed from a Young’s Double Slit Experiment would look like this.
- The bright areas represent constructive interference.
- The dark areas represent destructive interference.

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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.
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.

This is destructive interference.

- A dark fringe occurs
Interference Equations

- The path difference, \( \delta \), is found from the tan triangle
- \( \delta = r_2 - r_1 = d \sin \theta \)
  - This assumes the paths are parallel
  - Not exactly parallel, but a very good approximation since \( L \) is much greater than \( d \)

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Interference Equations, 2

- For a bright fringe, produced by constructive interference, the path difference must be either zero or some integral multiple of the wavelength

\[ \delta = d \sin \theta_{\text{bright}} = m \lambda \]

- \( m = 0, \pm 1, \pm 2, \ldots \)
- \( m \) 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
The positions of the fringes can be measured vertically from the zeroth order maximum.

\[ y = L \tan \theta \approx L \sin \theta \]

Assumptions

- \( L >> d \)
- \( d >> \lambda \)

Approximation

- \( \theta \) is small and therefore the approximation \( \tan \theta \approx \sin \theta \) can be used
When destructive interference occurs, a dark fringe is observed. This needs a path difference of an odd half wavelength. 

\[ \delta = d \sin \theta_{\text{dark}} = (m + \frac{1}{2}) \lambda \]

- \( m = 0, \pm 1, \pm 2, \ldots \)
Interference Equations, final

- For bright fringes

- For dark fringes

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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.

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Lloyd’s Mirror

- An arrangement for producing an interference pattern with a single light source
- Wave reach point P either by a direct path or by reflection
- The reflected ray can be treated as a ray from the source S’ behind the mirror

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Interference Pattern from the Lloyd’s Mirror

- An interference pattern is formed
- The positions of the dark and bright fringes are reversed relative to pattern of two real sources
- This is because there is a 180° phase change produced by the reflection
Phase Changes Due To Reflection

- An electromagnetic wave undergoes a phase change of 180° upon reflection from a medium of higher index of refraction than the one in which it was traveling.
  - Analogous to a reflected pulse on a string.

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Phase Changes Due To Reflection, cont

- There is no phase change when the wave is reflected from a boundary leading to a medium of lower index of refraction
  - Analogous to a pulse in a string reflecting from a free support

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Interference in Thin Films

- Interference effects are commonly observed in thin films
  - Examples are soap bubbles and oil on water
- The interference is due to the interaction of the waves reflected from both surfaces of the film
Interference in Thin Films,

2

Facts to remember

- An electromagnetic wave traveling from a medium of index of refraction $n_1$ toward a medium of index of refraction $n_2$ undergoes a $180^\circ$ phase change on reflection when $n_2 > n_1$
  - There is no phase change in the reflected wave if $n_2 < n_1$
- The wavelength of light $\lambda_n$ in a medium with index of refraction $n$ is $\lambda_n = \lambda/n$ where $\lambda$ is the wavelength of light in vacuum

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Interference in Thin Films,

- Ray 1 undergoes a phase change of 180° with respect to the incident ray.
- Ray 2, which is reflected from the lower surface, undergoes no phase change with respect to the incident wave.
Ray 2 also travels an additional distance of $2t$ before the waves recombine.

For constructive interference:
- $2nt = (m + \frac{1}{2}) \lambda \quad m = 0, 1, 2 \ldots$
  - This takes into account both the difference in optical path length for the two rays and the $180^\circ$ phase change.

For destructive interference:
- $2nt = m \lambda \quad m = 0, 1, 2 \ldots$
Interference in Thin Films, 5

- Two factors influence interference
  - Possible phase reversals on reflection
  - Differences in travel distance
- The conditions are valid if the medium above the top surface is the same as the medium below the bottom surface
- 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

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Interference in Thin Films, final

- Be sure to include two effects when analyzing the interference pattern from a thin film
  - Path length
  - Phase change

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Newton’s Rings

- Another method for viewing interference is to place a planoconvex lens on top of a flat glass surface.
- The air film between the glass surfaces varies in thickness from zero at the point of contact to some thickness $t$.
- A pattern of light and dark rings is observed.
  - This rings are called *Newton’s Rings*.
  - The particle model of light could not explain the origin of the rings.
- Newton’s Rings can be used to test optical lenses.

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Problem Solving Strategy with Thin Films, 1

- Identify the thin film causing the interference
- Determine the indices of refraction in the film and the media on either side of it
- Determine the number of phase reversals: zero, one or two
The interference is constructive if the path difference is an integral multiple of $\lambda$ and destructive if the path difference is an odd half multiple of $\lambda$. 

The conditions are reversed if one of the waves undergoes a phase change on reflection.
### Problem Solving with Thin Films, 3

<table>
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<th>Equation</th>
<th>1 phase reversal</th>
<th>0 or 2 phase reversals</th>
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<tr>
<td>$2nt = (m + \frac{1}{2}) \lambda$</td>
<td>constructive</td>
<td>destructive</td>
</tr>
<tr>
<td>$2nt = m \lambda$</td>
<td>destructive</td>
<td>constructive</td>
</tr>
</tbody>
</table>
Interference in Thin Films, Example

- An example of different indices of refraction
- A coating on a solar cell
- There are two phase changes