Fluids, Thermodynamics, Waves, & Optics
Optics
Lab 9
Interference and Diffraction

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Overview

- Purpose
- Theory
  - interference from two coherent light sources
  - diffraction from a single light source
  - interference and diffraction
- Part 3.1: Viewing diffraction patterns in the simulation
- Part 3.2: Single slit diffraction
- Part 3.3: Two slit interference with diffraction

Purpose of the Lab

To investigate the wave nature of light.

You will use a laser on an optical bench and screens to study diffraction and interference patterns.

You will

1. use the Wave Interference PhET simulation
2. observe a single slit diffraction pattern and calculate the slit width from the observed pattern.
3. observe a two-slit pattern and calculate the slit separation and slit widths.

Moving beyond Ray Optics

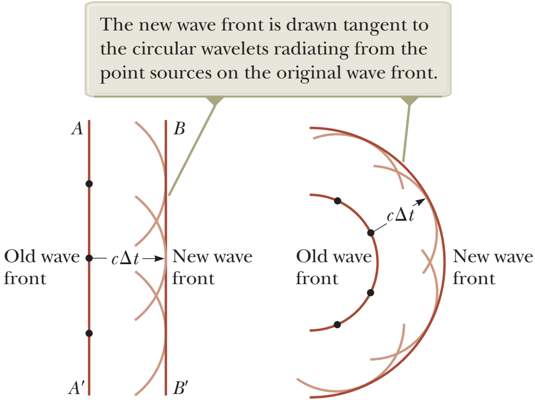
Ray optics can tell us about the formation of images, but it cannot tell us about the behavior of light that is specific to waves.

The ray approximation assumes that light will travel out from a source in straight lines, unless it encounters a change of medium.

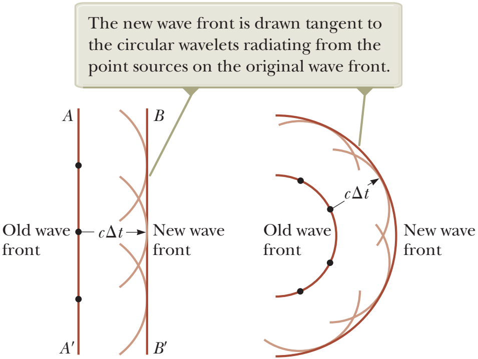
However light does also behave a wave and can change direction at apertures: diffraction and interference.

Huygens' Principle

This is a geometric principle to construct a wavefront at a later point in time from a wavefront at an earlier one.



Huygens' Principle



Huygens' Principle

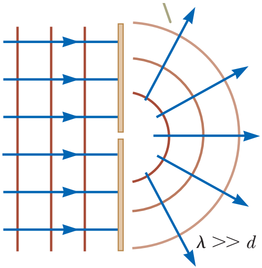
Every point on a propagating wavefront can be thought of as the source of a new spherical secondary wavelet. The wavefront formed at a later time is the surface tangent (or envelope) of all these wavelets.

Huygens' Principle

Huygens' motivation for this principle was the idea of the existence of an ether: each part of the light wave would interact with particles composing the ether.

Now we know there is no ether.

This principle is still useful, since it gives us the correct idea of what happens in various circumstances, including diffraction.



[1]See pages 1072-3 in the textbook for a derivation of the law of reflection and Snell's Law from Huygens' Principle.

Huygens-Fresnel Principle

Fresnel added the concept of **interference** to Huygens' Principle, which explained the paths that rays of light seem to take.

Kirchhoff then showed that this new Huygens-Frensel Principle was a consequence of the wave equation, so it can be expressed in a rigorous mathematical way.

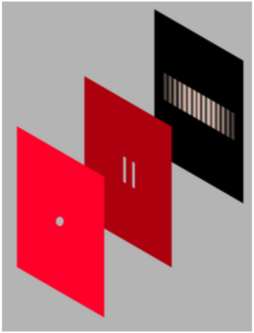
In fact, working from Kirchhoff's mathematical approach, this idea can be used to relate wavefronts at a light source to an image on a distant screen using Fourier Transforms.

Young's Double-Slit Experiment

Thomas Young in 1801 did the first experiment that conclusively showed the interference of light from 2 sources.

He filtered sunlight to make as source of red light, then shone the light through a series of narrow apertures (slits).

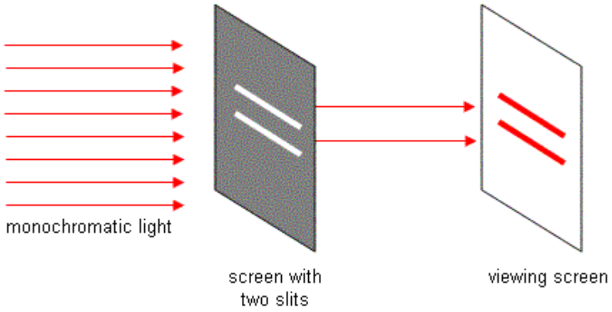
The first screen blocks all but tiny source of light. This is called the collimating slit, and ensure the light reaching the other two slits will be coherent.



[1]http://www.lightandmatter.com/

Young's Double-Slit Experiment

If light could be modeled as a particle, then one would expect to see two bright patches, one for each slit.

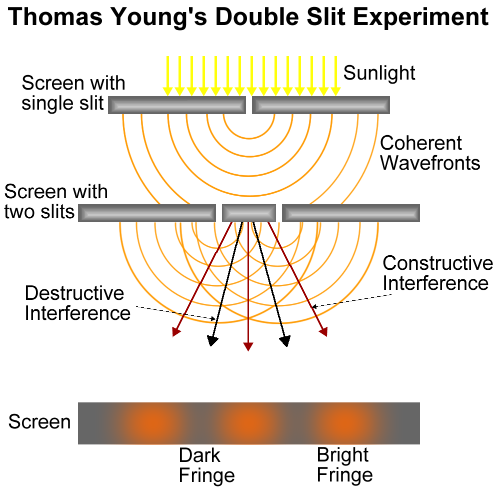


This is not what Young observed.

[1] http://www.studyphysics.ca

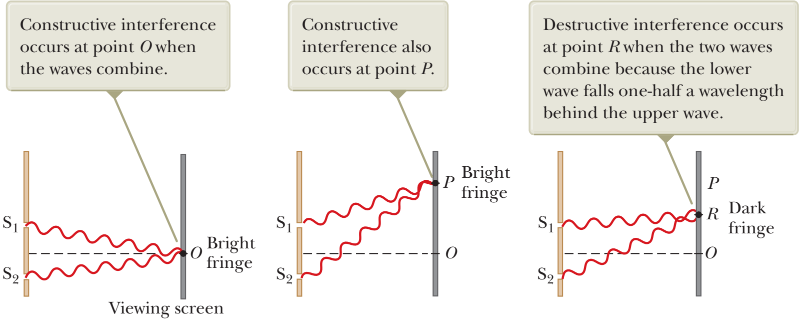
Young's Double-Slit Experiment

The filtered coherent light then goes through two slits cut from the same mask. The light from these two sources interferes.



The light strikes a screen where bright and dark areas can be seen.

Interference of Light



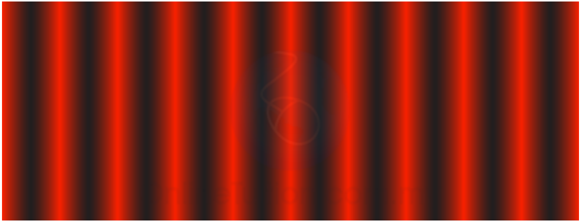
In places where the path lengths differ by a whole number of wavelengths ($m\lambda$) there is constructive interference.

[1] Serway & Jewett.

Interference

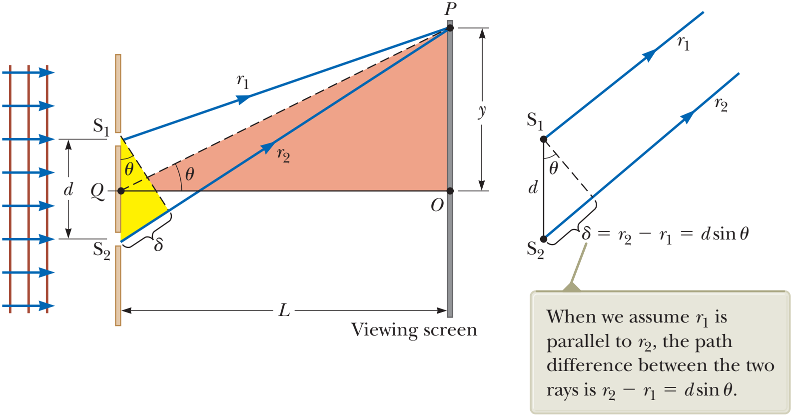
A pattern of light and dark "fringes" (stripes of light and darkness) appear on the screen.

Zoomed in view:



Interference: Finding the Maxima

For a distant screen and closely placed slits, the two rays are nearly parallel.



Looking at the right triangle with hypotenuse d (the slit separation distance): $\delta = d \sin \theta$.

Interference: Finding the Angles of the Maxima

Maxima (bright fringes) occur when

$$d \sin \theta_{\text{max}} = M \lambda \qquad \text{where } M \in \mathbb{Z}$$

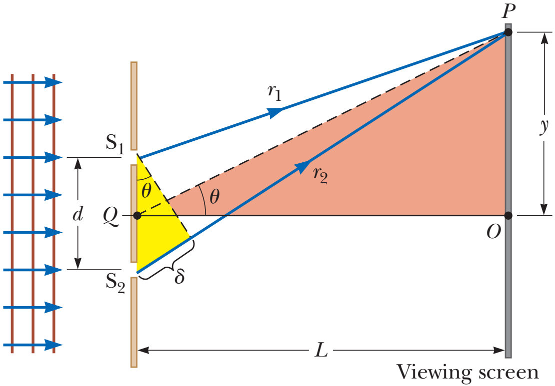
Minima (dark fringes) occur when

$$d \sin \theta_{\text{min}} = \left(M + \frac{1}{2} \right) \lambda \qquad \text{where } M \in \mathbb{Z}$$

These expressions give us the angles (measured outward from the axis that passes through the midpoint of the slits) where the bright and dark fringes occur.

Young's Experiment: Finding the Position of the Maxima

We can also predict the distance from the center of the screen, y, in terms of the distance from the slits to the screen, L.



$$\tan\theta = \frac{y}{L} \approx \sin\theta \quad \text{if } \theta \text{ is small}$$

Interference: Finding the Angles of the Maxima

Maxima (bright fringes) occur when y is such that:

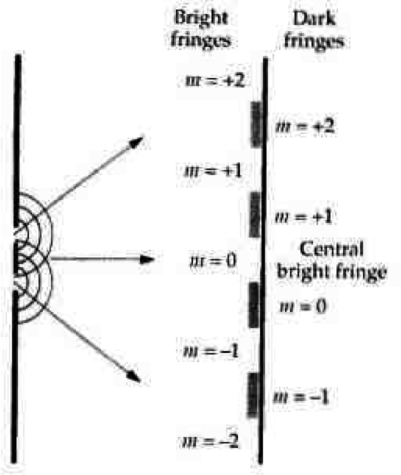
$$d = \frac{M \lambda L}{y} \qquad \text{where } M \in \mathbb{Z}$$

Minima (dark fringes) occur when y is such that:

$$d = \frac{\left(M + \frac{1}{2}\right) \lambda L}{y} \qquad \text{where } M \in \mathbb{Z}$$

These expressions give us the angles (measured outward from the axis that passes through the midpoint of the slits) where the bright and dark fringes occur.

Order Number

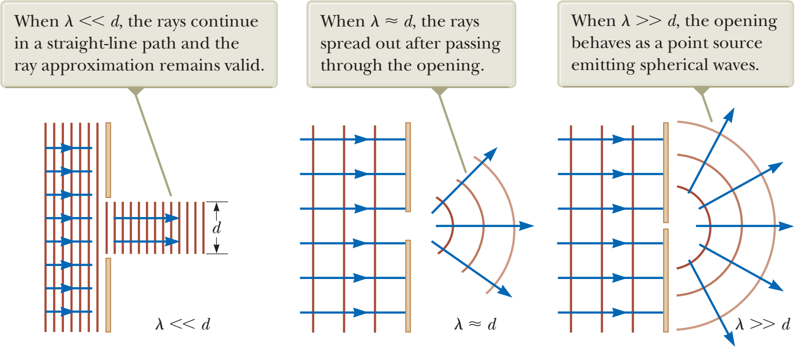


m is the order number. The central bright fringe is the "0th order fringe", the neighboring ones are the "1st order fringes", etc.

[1]Figure from Quantum Mechanics and the Multiverse by Thomas D. Le.

Diffraction

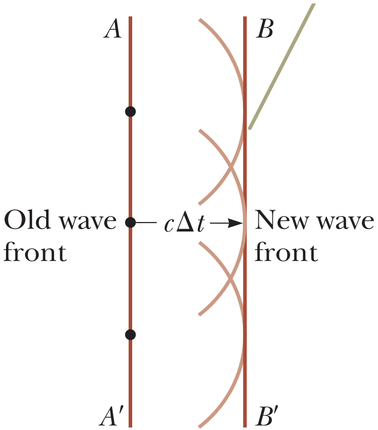
We already know that light and other waves that travel through a small gap ($< \lambda$) diverge, and that the smaller the gap, the more divergence.



The intensity of light in each direction is not the same however.

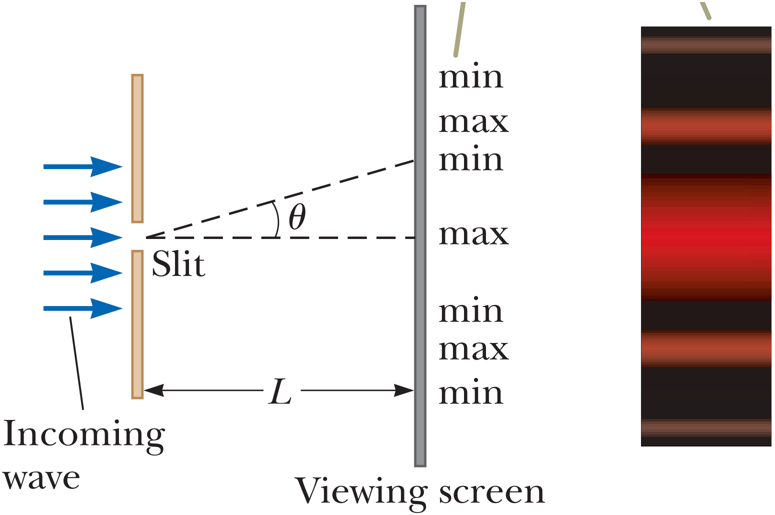
Diffraction and Huygens' Principle

When we have a slit or aperture illuminated by coherent light, each part of the aperture acts as a point source of spherical wavelets.



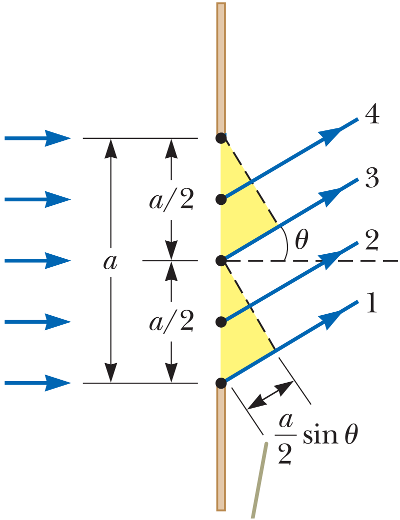
These wavelets interfere to produce a diffraction pattern.

Diffraction: Intensity Pattern from a Single Slit



Diffraction: Understanding the Single Slit Pattern

Consider a series of point sources in different parts of the slit. The slit has width *a*.



Diffraction: Understanding the Single Slit Pattern

We can find minima (dark fringes) in the pattern by breaking up our point sources into pairs that cancel each other out.

Matching point sources in the top half of the slit with ones in the bottom half, the source separation distances will be $d = a/2$.

This will be a fringe dark when:

$$\delta = \frac{a}{2} \sin \theta = \frac{\lambda}{2}$$

Diffraction: Understanding the Single Slit Pattern

However, we could also break the slit up into 4 equal parts and match sources from the 1st and 2nd, and match from the 3rd and 4th.

This will be dark when:

$$\delta = \frac{a}{4} \sin\theta = \frac{\lambda}{2}$$

If we break the slit up into 6 equal parts and match sources from the 1st and 2nd, the 3rd and 4th, and the 5th and 6th.

This will be dark when:

$$\delta = \frac{a}{6} \sin\theta = \frac{\lambda}{2}$$

Diffraction Minima

In general we expect dark fringes when:

$$a \sin \theta_{\text{min}} = m\lambda \qquad \text{where } m = \pm 1, \pm 2, \pm 3, \ldots$$

And if $\sin\theta \approx \frac{y}{L}$ then,

$$a = \frac{m\lambda L}{y}$$

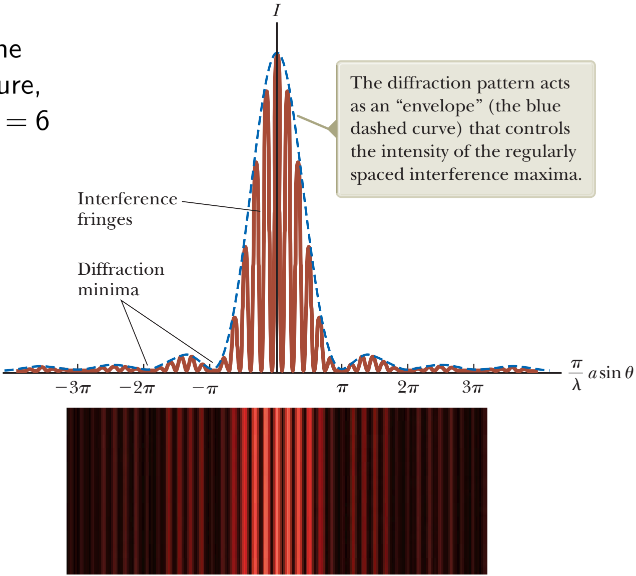
Interference AND Diffraction: Two slits that have some width

Suppose two slits each have width a and their centers are a distance d apart.

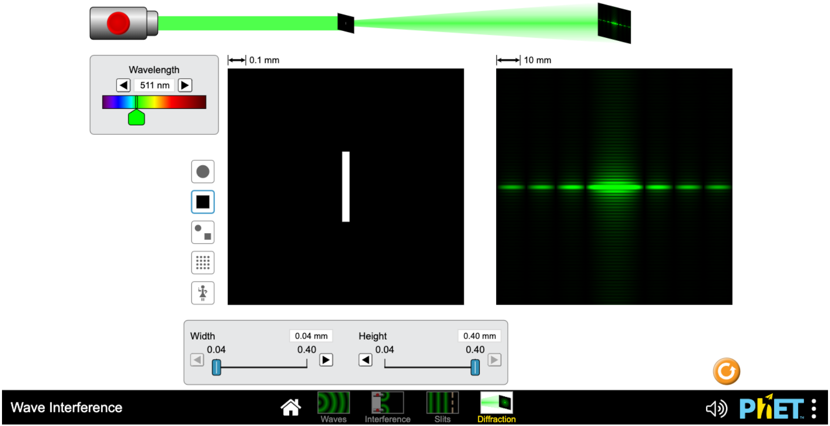
What intensity pattern do they create?

Interference AND Diffraction: Two slits that have some width

In the picture, $d/a = 6$

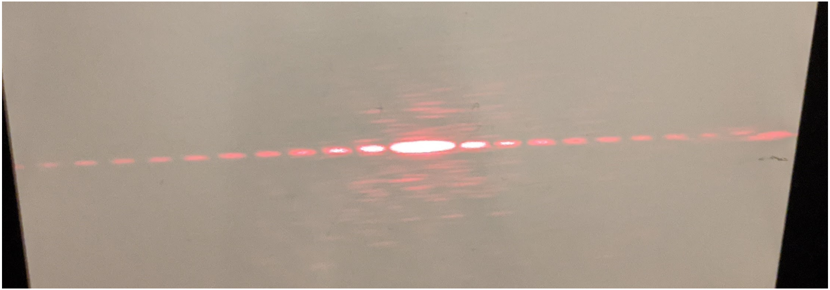


Part 3.1: Wave Interference Simulation

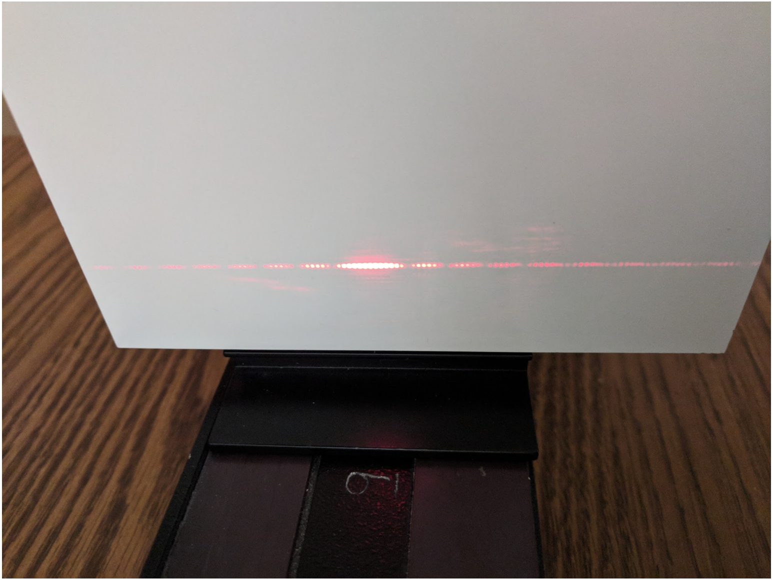


Parts 3.2&3: Equipment Setup

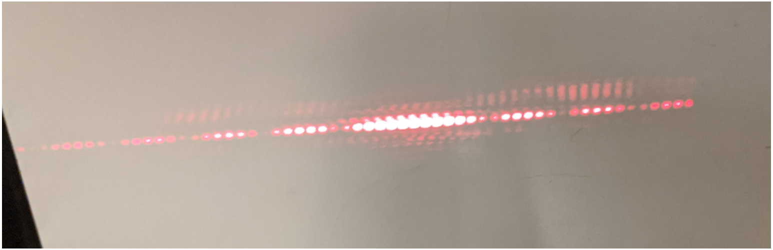
Diffraction Pattern



Interference and Diffraction Pattern



Interference and Diffraction Pattern



Standard error

standard error of the sample mean formula:

$$\text{s.e.}(a) = \sqrt{\frac{\sum_{i=1}^{N}(a_i - \bar{a})^2}{N(N-1)}}$$