Optics
Wave Behavior in Optics

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June 13, 2018

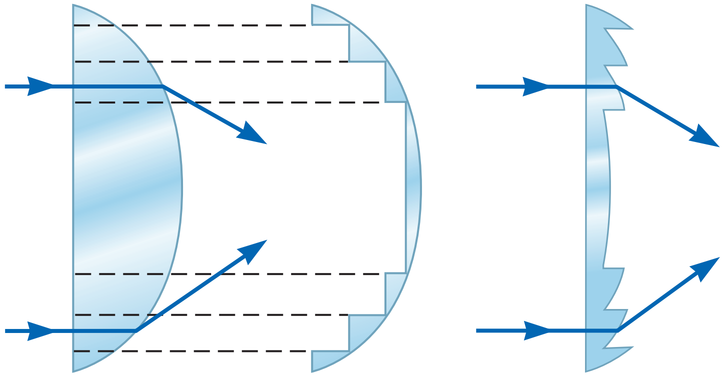
Last time

- images formed by lenses

Overview

- images formed by lens combinations
- Huygen's Principle
- Interference of light: the Double-Slit experiment

Fresnel Lenses



Combinations of Lenses

Two or more lenses can be used in series to produce and image.

This is used in

- eyeglasses (your eyeball lens is the second lens)
- refracting telescopes
- microscopes
- camera zoom lenses

Lenses can also be used together with curved mirrors, for example in reflecting telescopes.

Combinations of Lenses

Two thin lenses placed right up against each other (touching) will act like one lens with a focal length

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2}$$

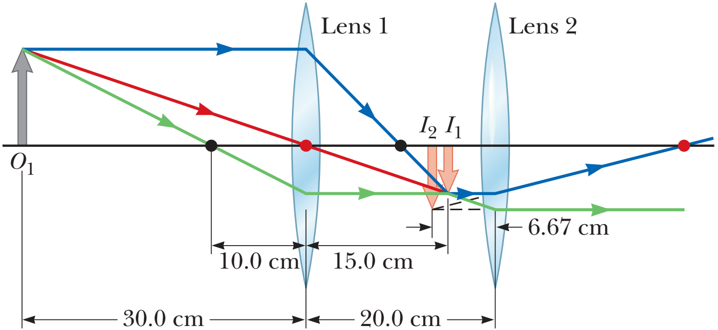
In other cases, the intermediate image formed by the first lens must be found, and imaged again in the second lens to find the final image.

The magnification of a series of lenses is the product of the magnification produced by each one.

Combinations of Lenses Example 36.10

Two thin converging lenses of focal lengths $f_1 = 10.0$ cm and $f_2 = 20.0$ cm are separated by 20.0 cm as illustrated. An object is placed 30.0 cm to the left of lens 1.

Find the position and the magnification of the final image.



One last aside: Permittivity and Refractive index

The relationship between the dielectric constant, κ, and the refractive index, n, is

$$n^2 = \kappa$$

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The wave equation for the E-field of light in a vacuum:

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \epsilon_0 \frac{\partial^2 E}{\partial t^2}$$

But in a (non-magnetic) material with a dielectric constant κ this becomes:

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So the new speed of the light wave in that material is

$$v = \frac{1}{\sqrt{\mu_0 \kappa \epsilon_0}}$$

$$n = \frac{c}{v} = \sqrt{\kappa}$$

Moving beyond Ray Optics

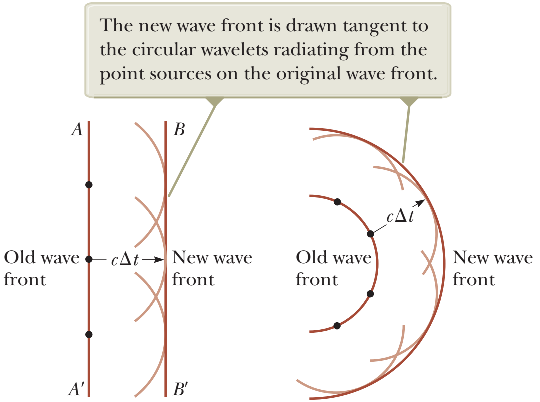
Ray optics can tell us about the formation of images, but it cannot tell us about the behavior of light that is specific to waves.

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

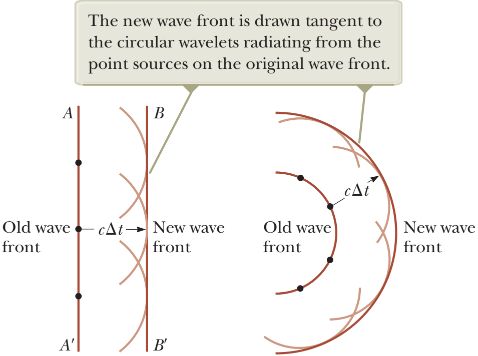
However light does also behave a wave and can change direction at apertures: diffraction and interference.

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

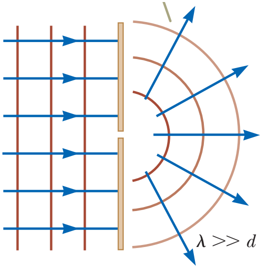
Every point on a propagating wavefront can be thought of as the source of a new spherical secondary wavelet. The wavefront formed at a later time is the surface tangent (or envelope) of all these wavelets.

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 page in the textbook for a derivation of 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.

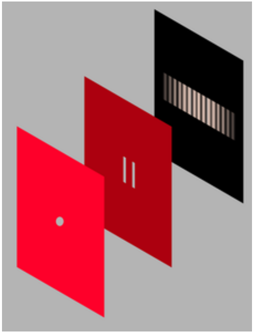
In fact, working from Kirchhoff's mathematical approach, this idea can be used to relate wavefronts at a light source to an image on a screen using Fourier Transforms.

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).

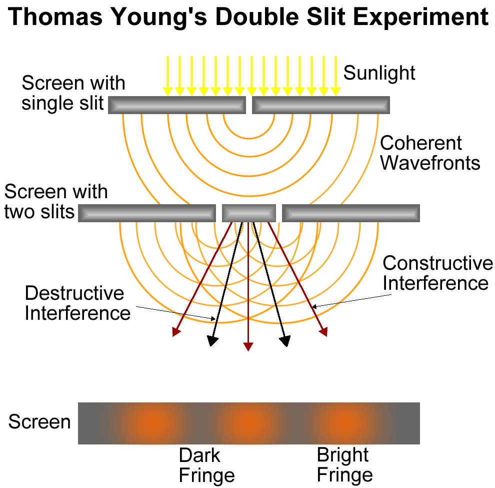
The first screen blocks all but tiny source of light. This is called the collimating slit, and ensure the light reaching the other two slits will be coherent.



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

Young's Double-Slit Experiment

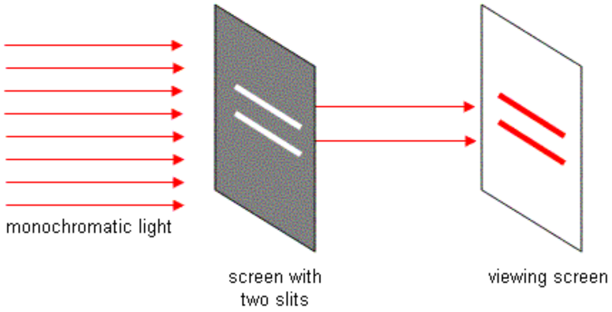
The filtered coherent light then goes through two slits cut from the same mask. The light from these two sources interferes.



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

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.



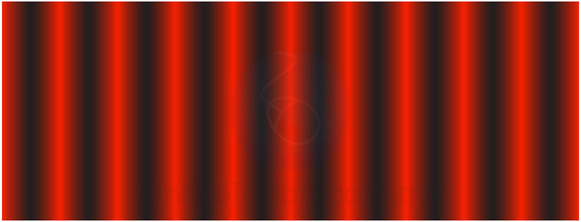
This is not what Young observed.

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

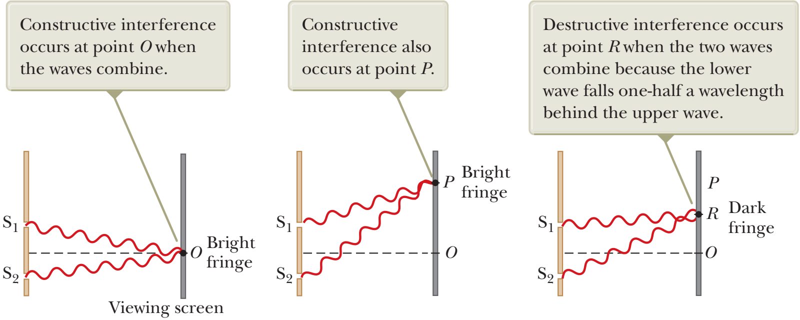
Young's Double-Slit Experiment

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

Zoomed in view:



Young's Experiment: Interference

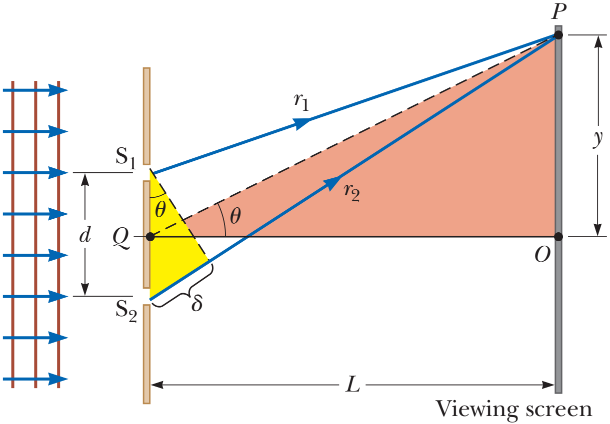


In places where the path lengths differ by a whole number of wavelengths ($m\lambda$) there is constructive interference.

[1]Serway & Jewett.

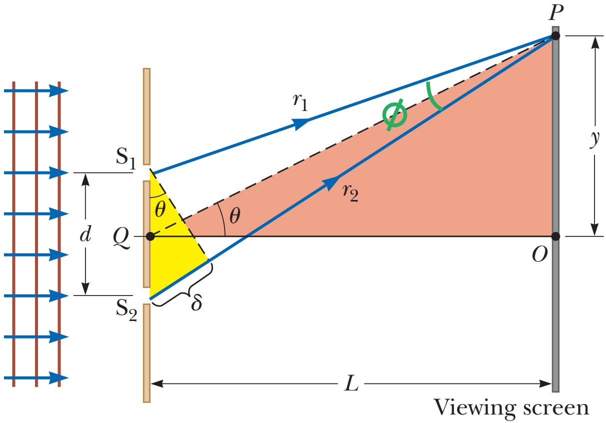
Young's Experiment: Finding the Maxima

Consider light that is diffracted through each slit at an angle $\approx \theta$.



Young's Experiment: Finding the Maxima

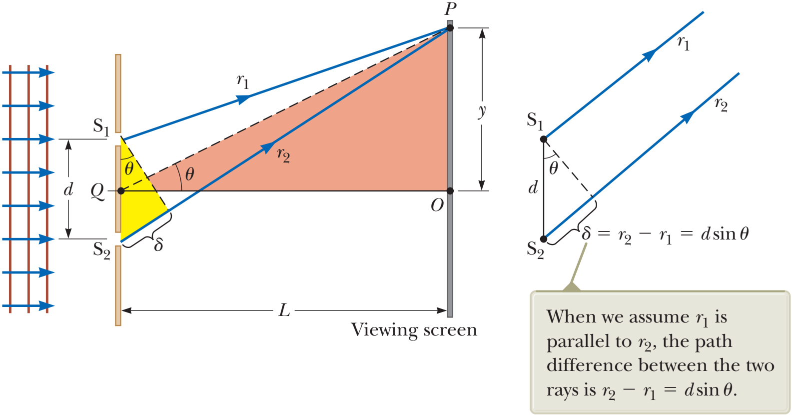
If the distance to the screen is very much larger that the distance between the slits (it will be), then ϕ is very small.



$\cos\phi \approx 1$ and $r_1 = r_2 - \delta$. The path difference is δ!

Young's Experiment: Finding the Maxima

Effectively, the two rays are parallel.



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

Young's Experiment: Finding the Angles of the Maxima

Maxima (bright fringes) occur when

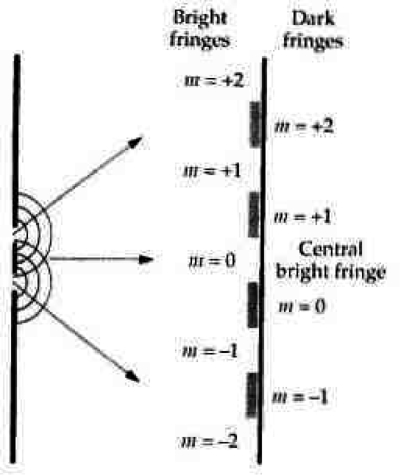
$$d \sin \theta_{\text{max}} = m\lambda \qquad \text{where } m \in \mathbb{Z}$$

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.

Order Number

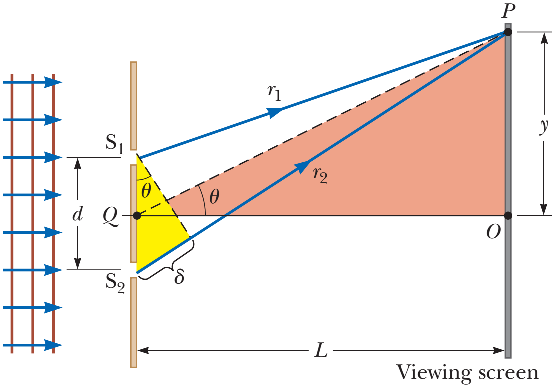


m is the order number. The central bright fringe is the "0th order fringe", the neighboring ones are the "1st order fringes", etc.

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

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.



$$\tan\theta = \frac{y}{L}$$

Young's Experiment: Finding the Position of the Maxima

Maxima (bright fringes) occur at

$$y_{\text{max}} = L \tan \theta_{\text{max}}$$

Minima (dark fringes) occur at

$$y_{\text{min}} = L \tan \theta_{\text{min}}$$

Young's Experiment: Finding the Position of the Maxima

When θ is also small, $\sin\theta \approx \tan\theta$, and we can use our earlier expressions for the fringe angles.

Maxima (bright fringes) occur at

$$y_{\text{max}} = L\,\frac{m\lambda}{d} \qquad \text{(small } \theta\text{)}$$

Minima (dark fringes) occur at

$$y_{\text{min}} = L\,\frac{\left(m + \frac{1}{2}\right)\lambda}{d} \qquad \text{(small } \theta\text{)}$$

Summary

- Huygen's principle
- two-slit interference

Collected Homework! due Monday, June 18.

Final Exam 9:15-11:15am, Tuesday, June 26.

Homework Serway & Jewett:

- Ch 37, onward from page 1150. OQs: 3, 9; CQs: 3, 5; Probs: 1, 3, 5, 13, 19, 21, 25, 51, 60