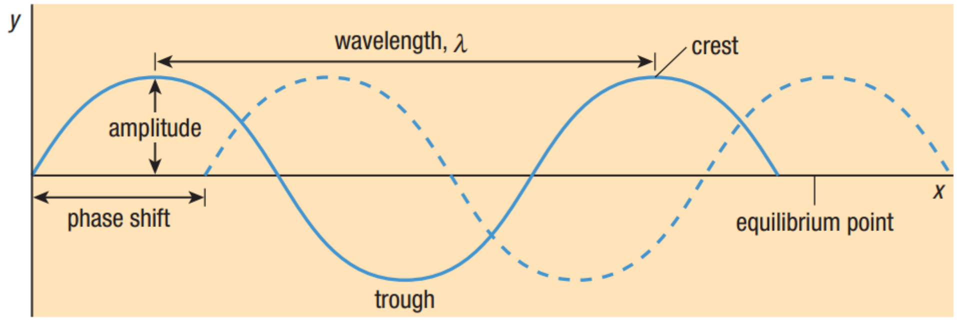
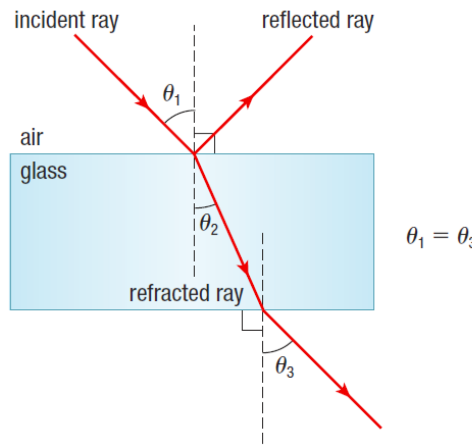


Medium	Index of refraction	Speed of light (m/s)	Medium	Index of refraction	Speed of light (m/s)
vacuum	1.00	2.9979×10^8	lens of human eye	1.41	2.1262×10^8
air	1.0003	2.9970×10^8	quartz crystal	1.46	2.0534×10^8
ice	1.30	2.3061×10^8	Pyrex glass	1.47	2.0394×10^8
liquid water	1.33	2.2541×10^8	Plexiglas (plastic)	1.51	1.9854×10^8
aqueous humour (liquid between the lens and cornea)	1.33	2.2541×10^8	benzene	1.50	1.9986×10^8
cornea of human eye	1.38	2.1724×10^8	zircon	1.92	1.5601×10^8
vitreous humour (liquid between the lens and retina)	1.38	2.1724×10^8	diamond	2.42	1.2388×10^8

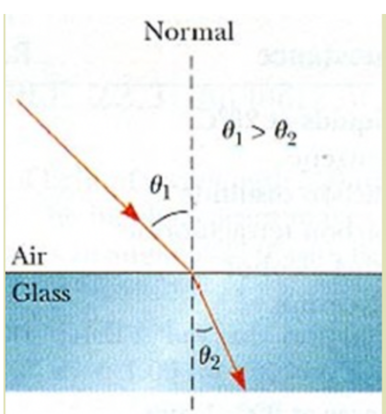


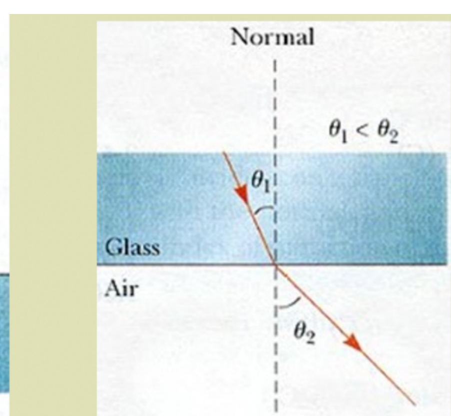
Refraction:

When we talk about the speed of light, we're usually talking about the speed of light in a vacuum, which is c = 3.00 x 10^8 m/s. When light travels through something else, such as glass, diamond, or plastic, it travels at a different speed. The speed of light in a given material is related to a quantity called the index of refraction, n, which is defined as the ratio of the speed of light in vacuum to the speed of light in the medium:

index of refraction : $n = c / v$

When light travels from one medium to another, the speed changes, as does the wavelength. This causes the refracted ray to bend in the second material, from it's original incident path in medium 1.





How can you determine which way light will bend when passing from one medium into another medium?#

more dense

When light crosses an interface into a medium with a higher index of refraction, the light bends towards the normal. Conversely, light traveling across an interface from higher n to lower n will bend away from the normal.

high density → low density

Snell's law: $n_1 \sin\theta_1 = n_2 \sin\theta_2$ or, equivalently, $\sin\theta_1 / \sin\theta_2 = v_1 / v_2$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

Example:
Light moves from a vacuum into a plate of glass with index of refraction 1.47. The angle of incidence is 40.0°.

a. Calculate the angle of refraction.

b. The light continues through the glass and emerges back into a vacuum. Calculate the angle of refraction when the light exits the glass.

c. Suppose the light exits into water instead of a vacuum. Calculate the angle of refraction for the light moving from glass into water ($n_{water} = 1.33$).

Example:
Light travels at 3.0 x 10^8 m/s. Laser light with a wavelength of 520 nm enters a sheet of plastic. The index of refraction for the plastic is 1.49.

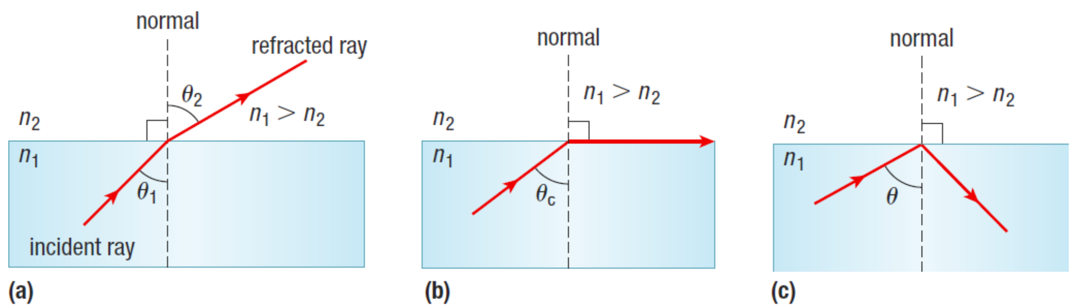
a. Calculate the speed of the laser light in the plastic.

b. Calculate the wavelength of the laser light in the plastic.

c. Calculate the frequency of the laser light in the plastic.

Total internal Reflection & Critical angle

This has an interesting implication: at some angle, known as the critical angle, light travelling from a medium with higher n to a medium with lower n will be refracted at 90°; in other words, refracted along the interface. If the light hits the interface at any angle larger than this critical angle, it will not pass through to the second medium at all. Instead, all of it will be reflected back into the first medium, a process known as total internal reflection.

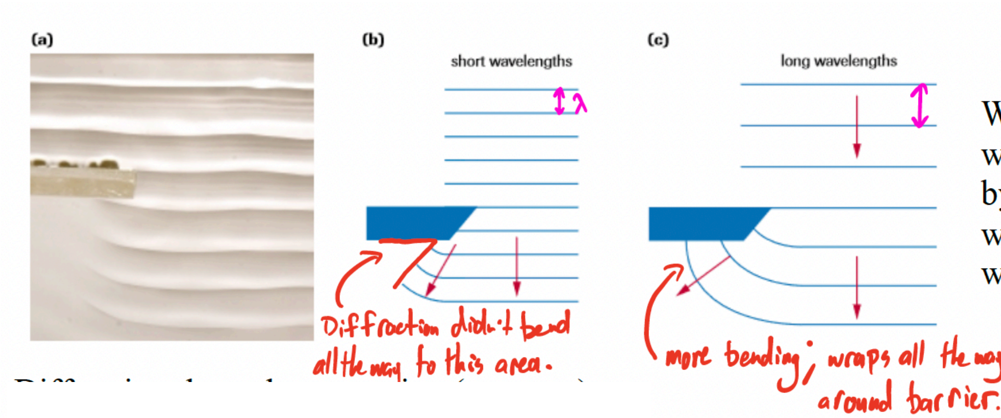


The critical angle can be found from Snell's law, putting in an angle of 90° for the angle of the refracted ray. This gives:

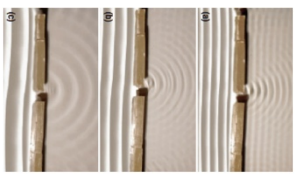
$$\text{critical angle}: \sin \theta_c = n_2 / n_1 \qquad (n_1 > n_2)$$

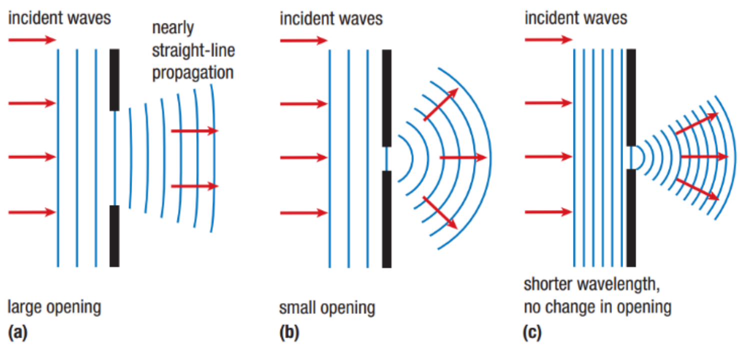
For any angle of incidence larger than the critical angle, Snell's law will not be able to be solved for the angle of refraction, because it will show that the refracted angle has a sine larger than 1, which is not possible. In that case all the light is totally reflected off the interface, obeying the law of reflection.

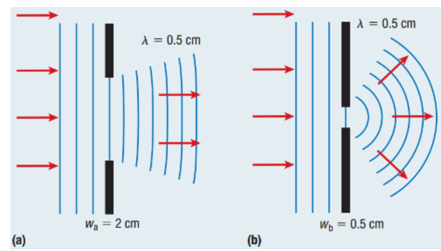
Diffraction of waves



Waves of longer wavelength are diffracted by a larger amount than waves with a smaller wavelength.



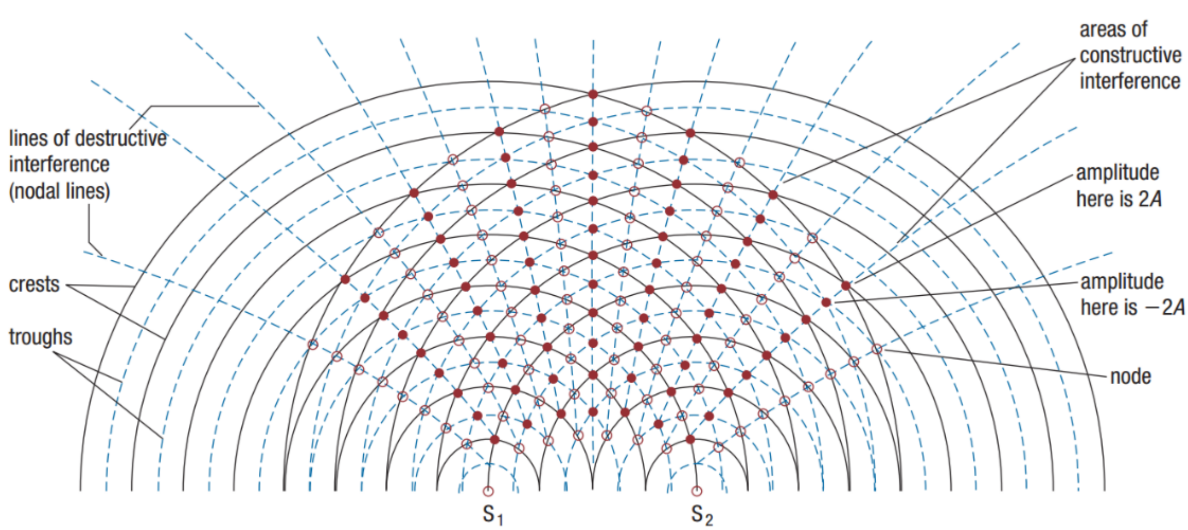


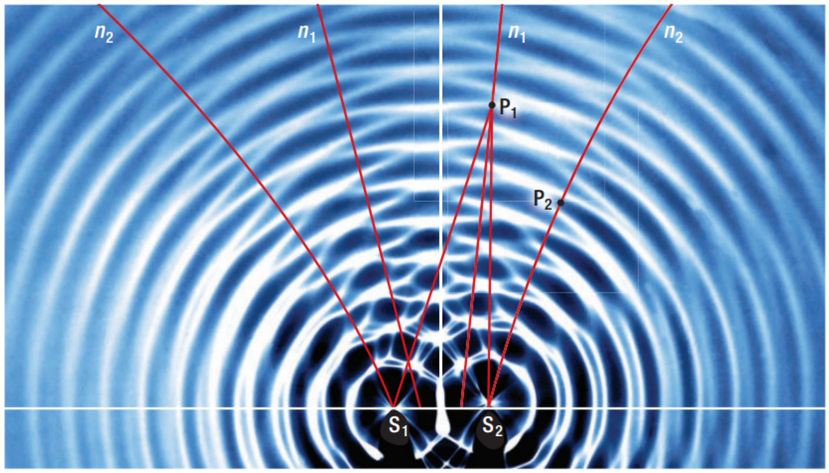


It must be that the width w ≤ λ for significant diffraction through an opening.

Interference of waves in 2D:

The interference pattern between waves from 2 point sources vibrating in phase:





Areas of destructive interference (where a crest meets a trough) create nodes. The pattern shows that nodes tend to 'line up' and create nodal lines that radiate away from the sources. Nodal lines are actually hyperbolas, but their curvature is so slight that we assume them to be linear for most calculations.

On either side of the nodal lines are areas of constructive interference (where either two crests or two troughs meet) that alternate between supercrests and supertroughs.

If the frequency of the sources increases, the wavelengths get smaller, and there is an increase in the number of nodal lines. Also, if the distance between the two sources increases, the number of nodal **lines** increases.

As you can see, the perpendicular bisector of the two sources (i.e. the line that goes straight out at 90^0 from the mid point of the imaginary line joining the sources) is a line of constructive interference. The first nodal line to either side of this is called n=1, the next nodal line n=2, and so on.

An important value in helping to determine the wavelength of the waves that produce such an interference pattern is something called the path length difference. It defines the difference in distances to each of the sources from any point (P) on a chosen nodal line (n). For nodal line n, this is written mathematically as $|P_nS_1 - P_nS_2|$ and the formula in which it is used is:

$$|P_nS_1 - P_nS_2| = \left(n - \frac{1}{2}\right)\lambda$$

Example: Two identical point sources are 5.0 cm apart, in phase, and vibrating at a frequency of 12 Hz. They produce an interference pattern. A point on the first nodal line is 5 cm from one source and 5.5 cm from the other.

a. Determine the wavelength.
b. Determine the speed of the waves.

Typically this formula is used by one taking measurements of both path lengths and then solving for the wavelength, but for waves of very small wavelength or very large distances to P, this method becomes inaccurate. In either of these cases we use mathematical approximations that hold true in the limit that $P_n \to \infty$ because P_nS_1 and P_nS_2 can be treated as if they were parallel. The derivation

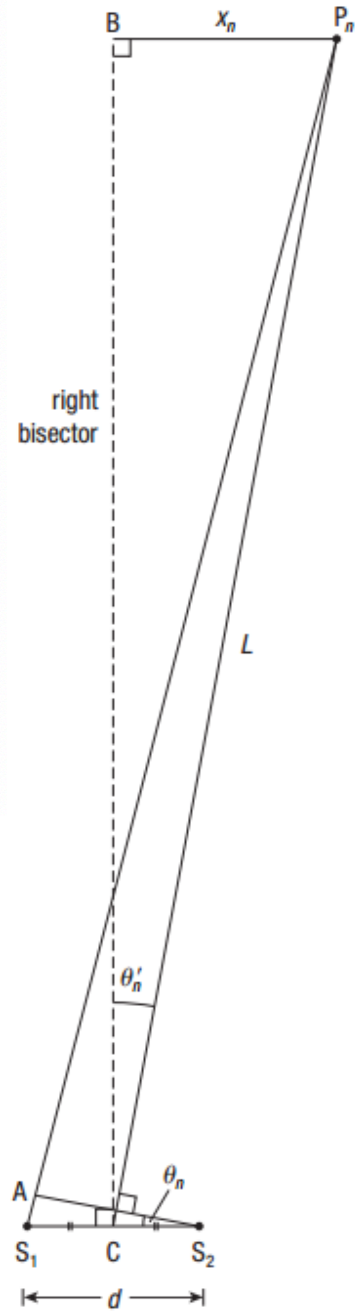
$$\sin \theta_n = \left(n - \frac{1}{2}\right)\frac{\lambda}{d}$$

A further derivation

$$\sin \theta_n = \frac{x_n}{L}$$

(where x_n is the perpendicular distance from the right bisector to the n^{th} nodal line, and L is the distance from the point P_n to the midpoint between the 2 sources – both measurable quantities). Therefore, we can also write:

$$\frac{x_n}{L} = \left(n - \frac{1}{2}\right)\frac{\lambda}{d}$$



Example: The distance from the right bisector to a point P on the second nodal line in a two-point interference pattern is 4.0 cm. The distance from the midpoint between the two sources, which are 0.5 cm apart, to point P is 14 cm.

a. Calculate the angle θ_2 for the second nodal line.

b. Calculate the wavelength.

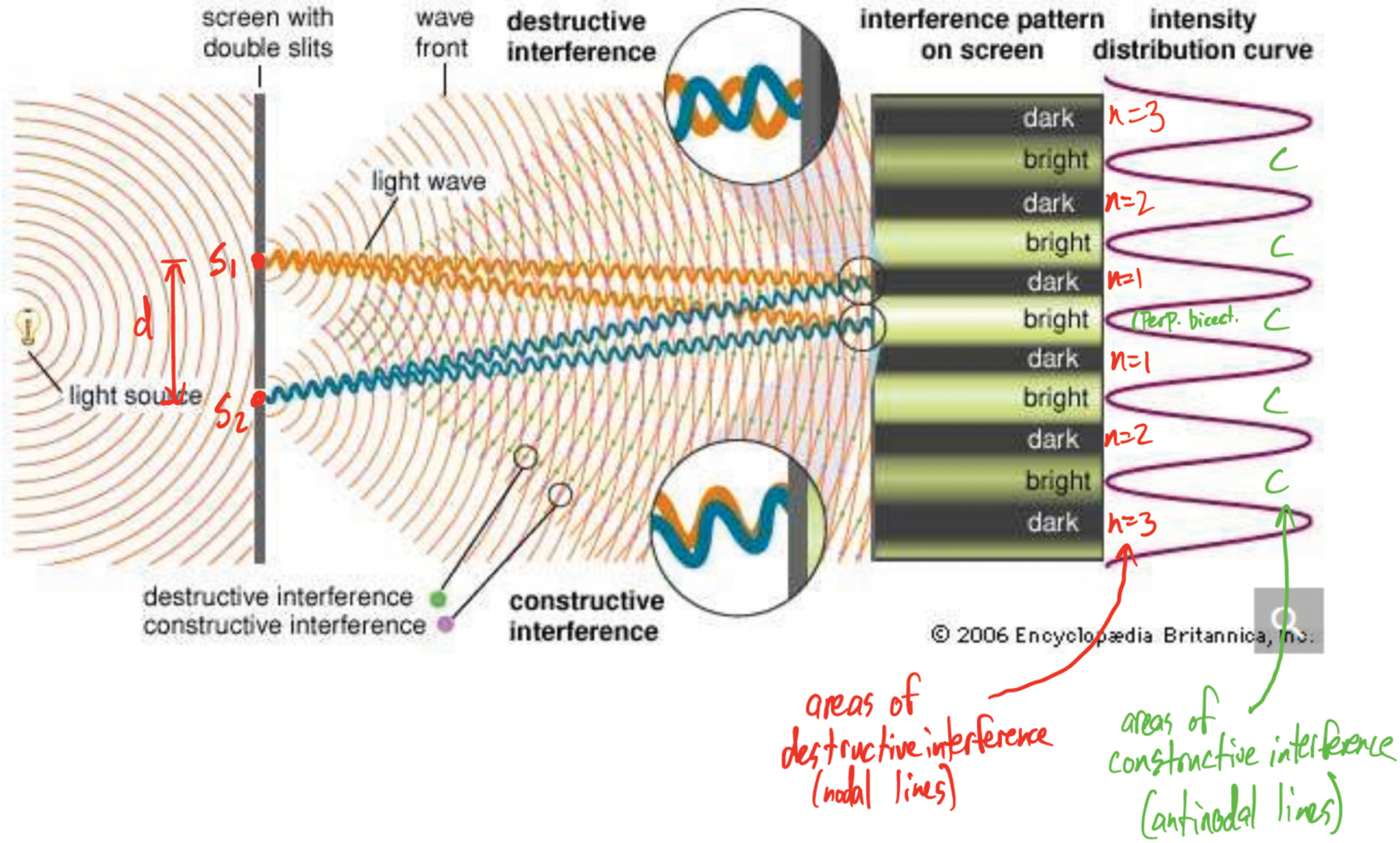
9.5 Wave interference: Young's Double Slit Experiment

With "light as a wave" being the most scientifically reasonable theory, many scientists tried to prove its validity by showing that light waves from 2 separate sources would produce an interference pattern like that of water waves in a tank.

For 2 reasons, it was impossible to find this "proof":
The wavelength of light is so small that adjacent nodal lines would have been indistinguishable (by the human eye, or even under microscope inspection).
Because scientists were using 2 separate light sources the light waves were out of phase with one another, producing an ever-changing interference pattern.

Young's experiments (1802-1804) used a single incandescent source of light (the Sun) that was directed through 2 very close pinholes in a thin opaque material. The light diffracted as it passed through each hole (Fig.2, p470), thereby creating 2 separate light sources that were both in phase and very close to each other. This produced a single fixed interference pattern that could be projected onto a screen.

The pattern was a series of successive light and dark bands. These are generally referred to as interference fringes. More specifically, the light/bright areas caused by constructive interference of the light waves are called maxima (singular: maximum) and the dark areas caused by destructive interference are called minima (singular: minimum).


screen with double slits
wave front
destructive interference
interference pattern on screen
intensity distribution curve
light wave
light source
dark
bright
dark
bright
dark
bright
dark
bright
dark
bright
dark
destructive interference
constructive interference
constructive interference
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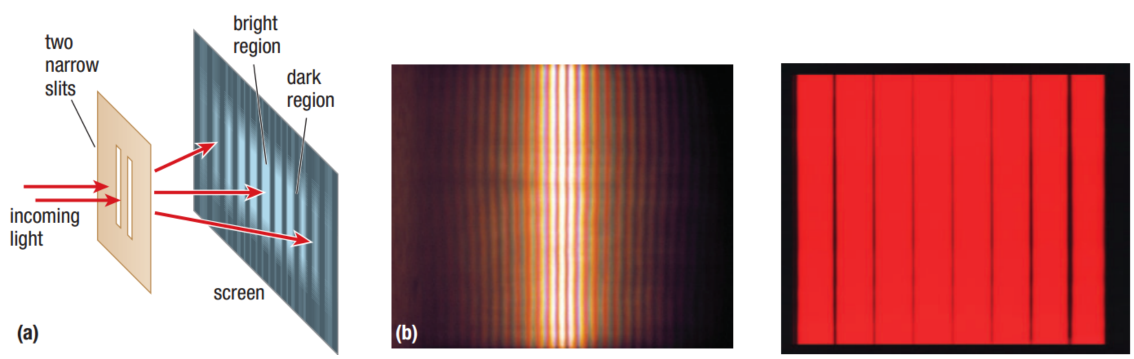
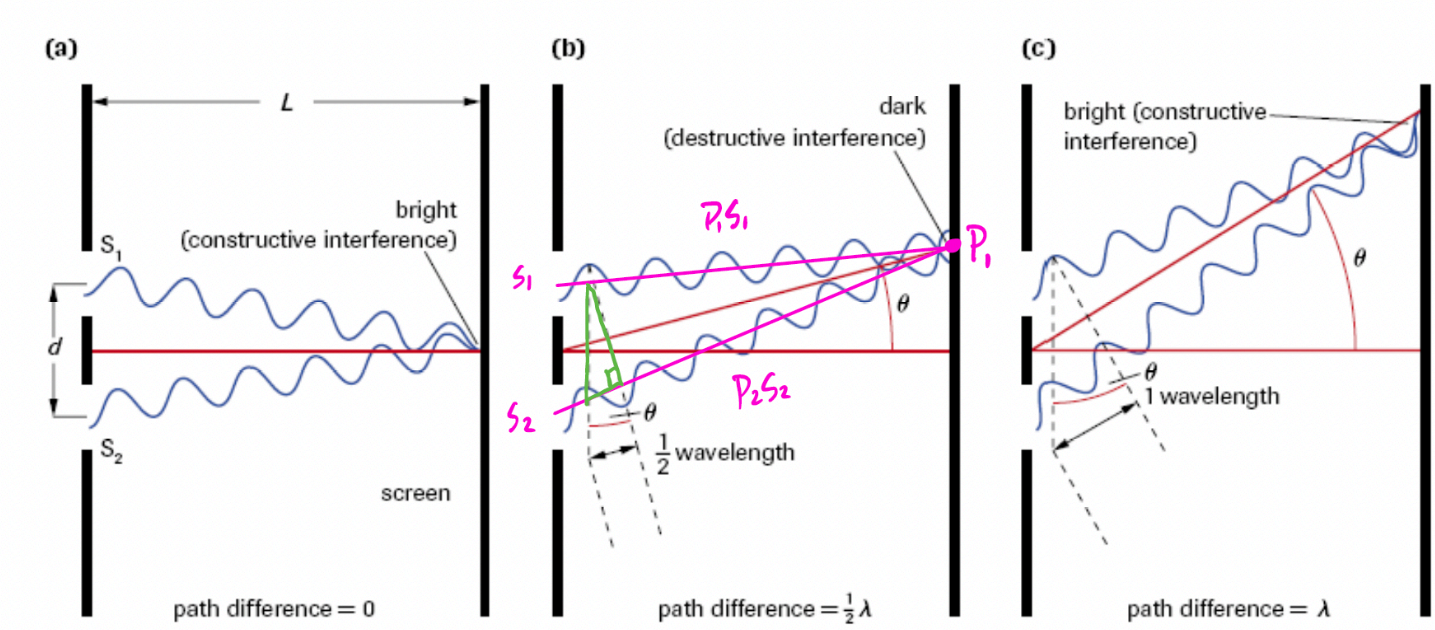
S1
S2
d
n=3
n=2
n=1
n=1
n=2
n=3
C
(Perp. bisect.
areas of destructive interference (nodal lines)
areas of constructive interference (antinodal lines)


two narrow slits
bright region
dark region
incoming light
screen
(a)
(b)

A good visual of how these maxima and minima are created is given below.



Light waves constructively interfere at the center of the screen, producing the brightest maximum (the central maximum).
Light waves destructively interfere at the screen, producing the first-order minimum (dark spot).
Light waves constructively interfere at the screen, producing the second-order maximum.

This pattern continues producing an interference fringe pattern of bright and dark spots with each successive maximum having less intensity (because the light waves are traveling farther before they reach the screen). Hence, light behaves like a wave creating an interference pattern.

Just like in ~~9.3~~ 4.05 since light acts like a wave and is ~~prucing~~ producing an interference pattern, we can use the interference equations for the nodal lines (which correspond to the minima seen on the screen or dark spots on the screen) given by:

$$\sin \theta_n = \frac{x_n}{L} = \left(n - \frac{1}{2}\right)\frac{\lambda}{d}$$

$$x_n = \left(n - \frac{1}{2}\right)\frac{L\lambda}{d}$$

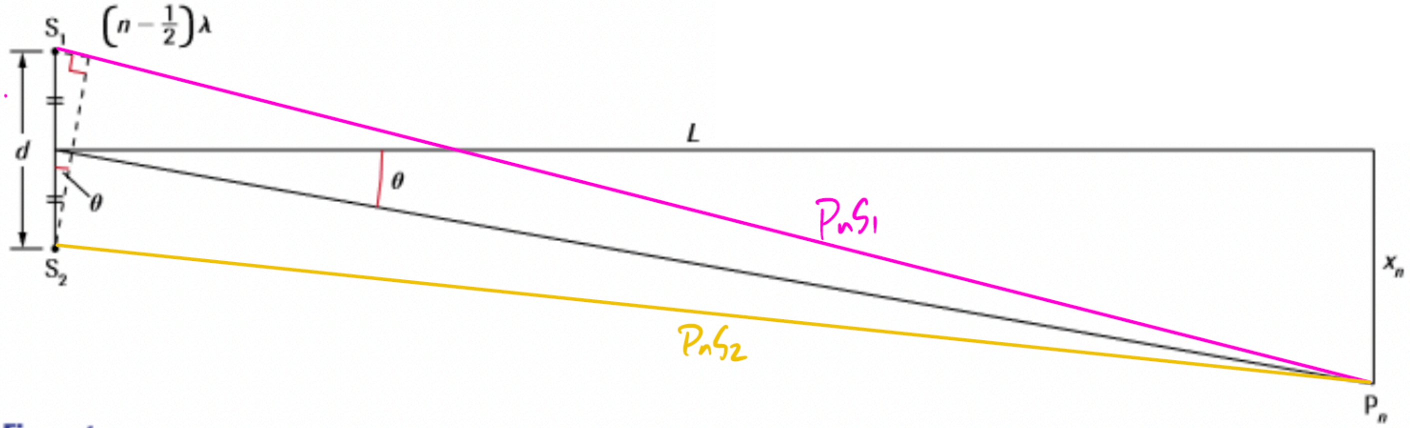


Figure 4

For each nodal line n = 1, 2, 3 we can derive a separate value for x from the above equation:

$$x_n = \left(n - \frac{1}{2}\right)\frac{L\lambda}{d}$$

$$x_1 = \left(1 - \frac{1}{2}\right)\frac{L\lambda}{d} = \frac{L\lambda}{2d}$$

$$x_2 = \left(2 - \frac{1}{2}\right)\frac{L\lambda}{d} = \frac{3L\lambda}{2d}$$

$$x_3 = \left(3 - \frac{1}{2}\right)\frac{L\lambda}{d} = \frac{5L\lambda}{2d}$$

etc.

This shows that the displacement between adjacent nodal lines (Δx) is given by

$$\frac{\Delta x}{L} = \frac{\lambda}{d}$$

Where the spacing on the screen between any two adjacent nodal lines is Δx, the distance from the sources to the screen is L, and the distance between the sources d.

Example: A double-slit experiment is carried out with slit spacing $d = 0.41$ mm. The screen is at a distance of 1.5 m. The bright fringes at the centre of the screen are separated by a distance of $\Delta x = 1.5$ mm. Calculate the wavelength of the light.

Example: The third-order dark fringe of 660 nm light is observed at an angle of 20.0° when the light falls on two narrow slits. Determine the slit distance.