Chapter 28 Physical Optics and Diffraction

28.1 Superposition and Interference

28.2 Young’s Two-Slit Experiment

28.3 Interference in Reflected Waves

28.4 Diffraction

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Being a wave, light can exhibit effects due to interference and diffraction. The study of the interference and diffraction of light is referred to as **wave optics** or **physical optics**, to distinguish it from **geometrical optics**, which deals with the straight-line motion of light and its reflection and refraction. In this chapter, we will study the wave nature of light.

Linear superposition of light waves

According to the *principle of linear superposition*, two or more light waves can interfere constructively or destructively when they exist at the same place at the same time, provided they originate from *coherent sources*.

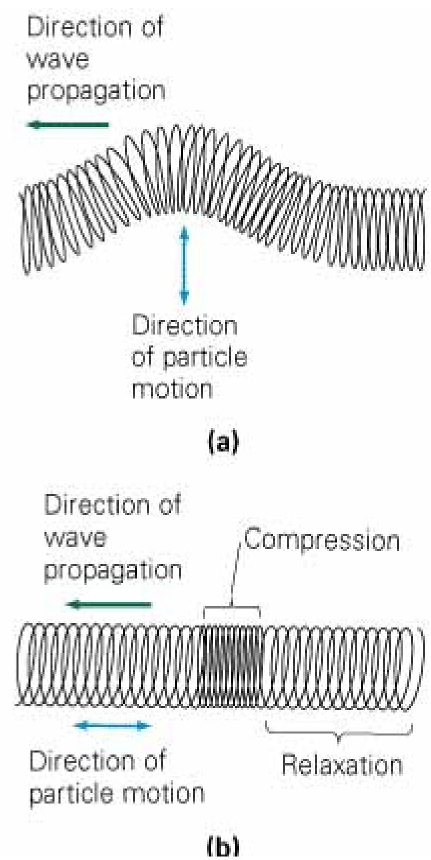
Coherent source

Two sources are coherent if they emit waves that have a constant phase relationship.

Light moving in straight lines:
Geometrical Optics
Light is a wave. Wave aspects of light:
physical optics.

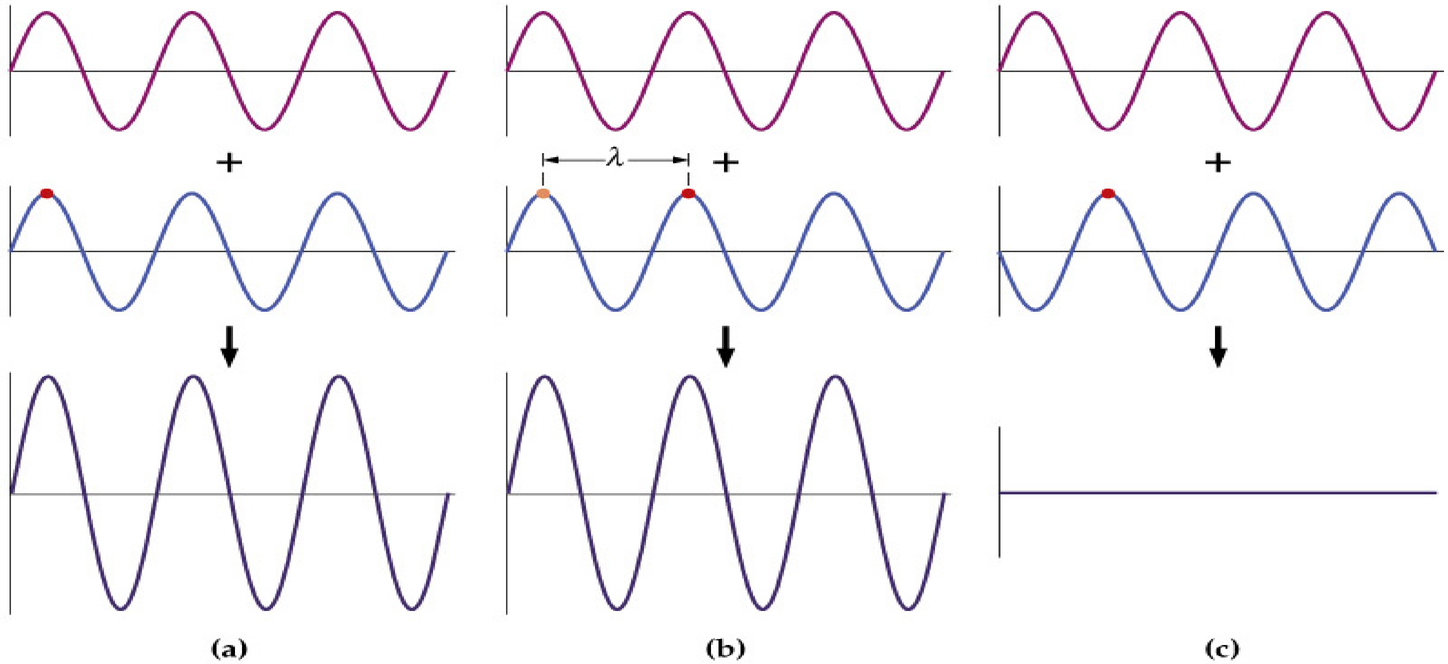
Light is a transverse electromagnetic wave. Therefore light should display phenomena that are characteristic of waves. (Interference and diffraction)
Conversely (historically), the observation of light interference or diffraction proves that we are dealing with a wave.

Transverse wave



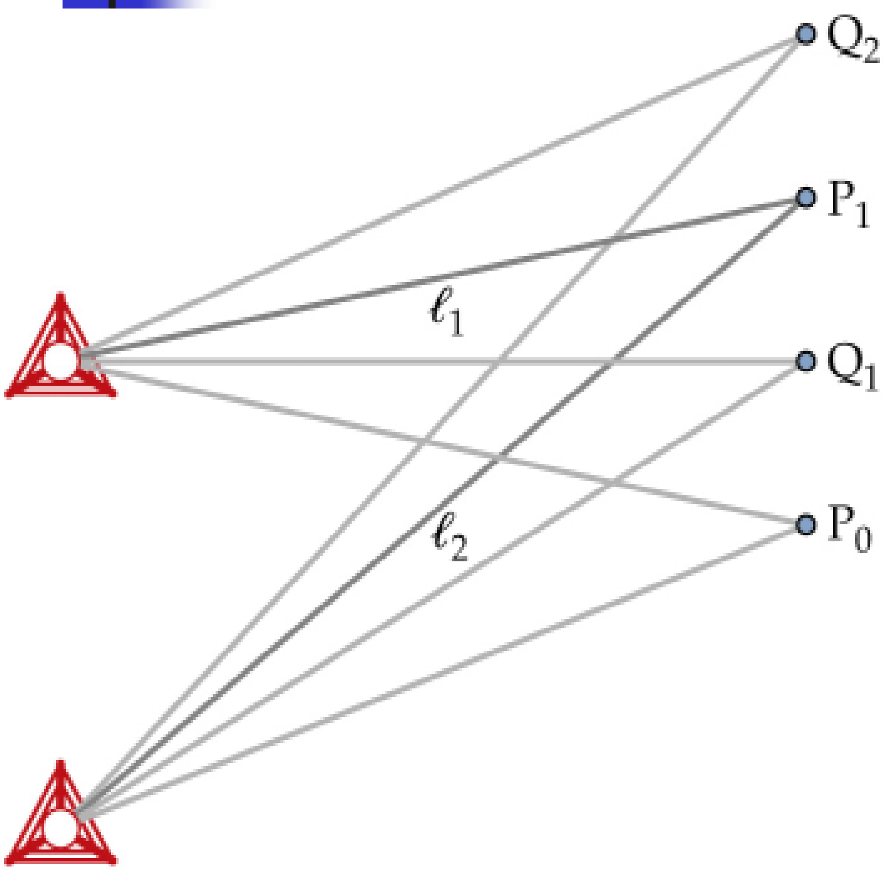
Longitudinal wave

Figure 28–1 Constructive and destructive interference



- (a) Waves that are in phase add to give a larger amplitude. This is constructive interference. (b) If waves are one wavelength out of phase, the result is still constructive interference. (c) Waves that are half a wavelength out of phase interfere destructively.

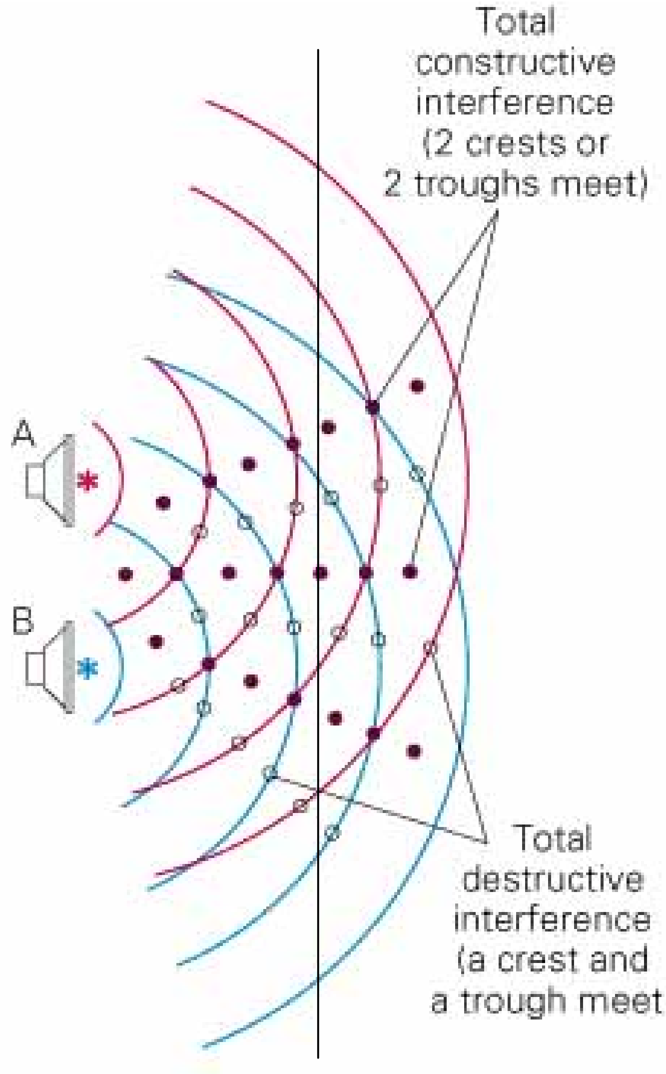
Figure 28–2 Two radio antennas transmitting the same signal



At point P_0, midway between the antennas, the waves travel the same distance, and hence they interfere constructively. At point P_1 the distance ℓ_2 is greater than the distance ℓ_1 by one wavelength; thus, P_1 is also a point of constructive interference. At Q_1 the distance ℓ_2 is greater than the distance ℓ_1 by half a wavelength, and the waves interfere destructively at that point.

Waves can interfere constructively or destructively

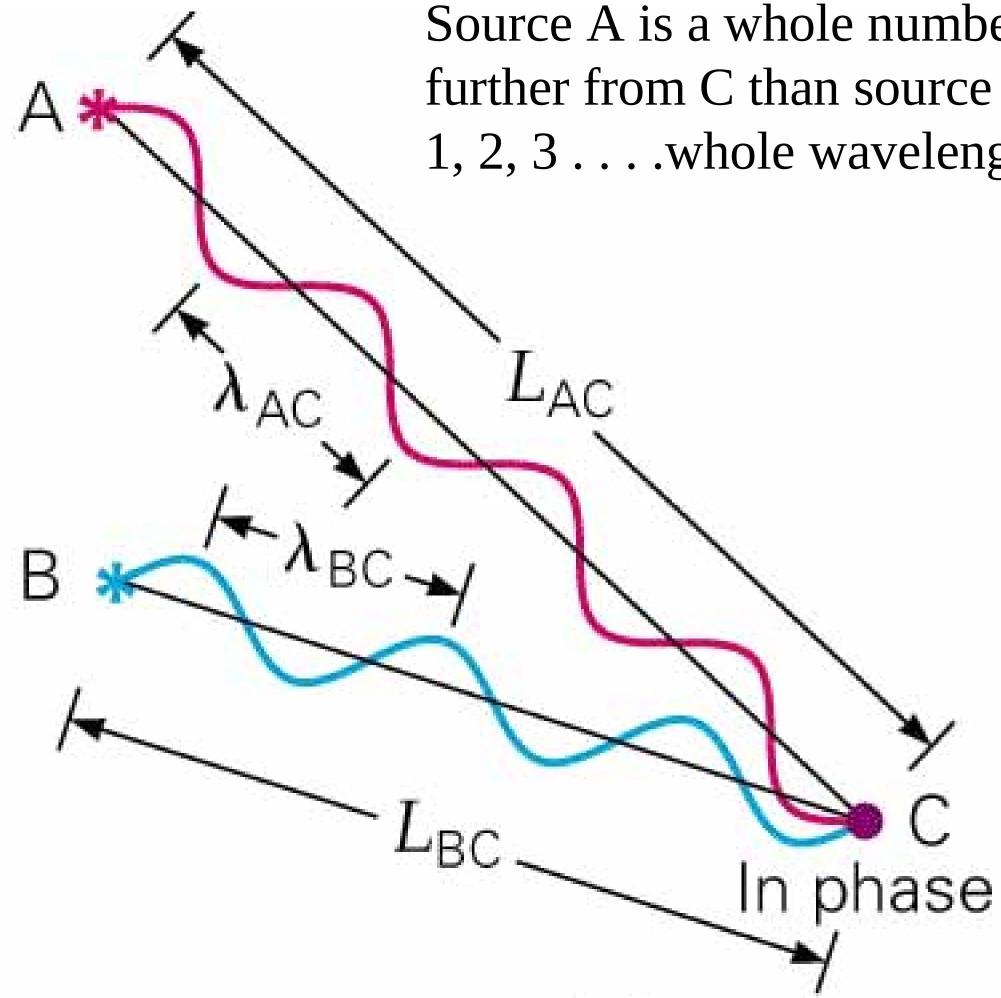
What would happen if you walked along the line shown?



(a)

Waves can interfere constructively

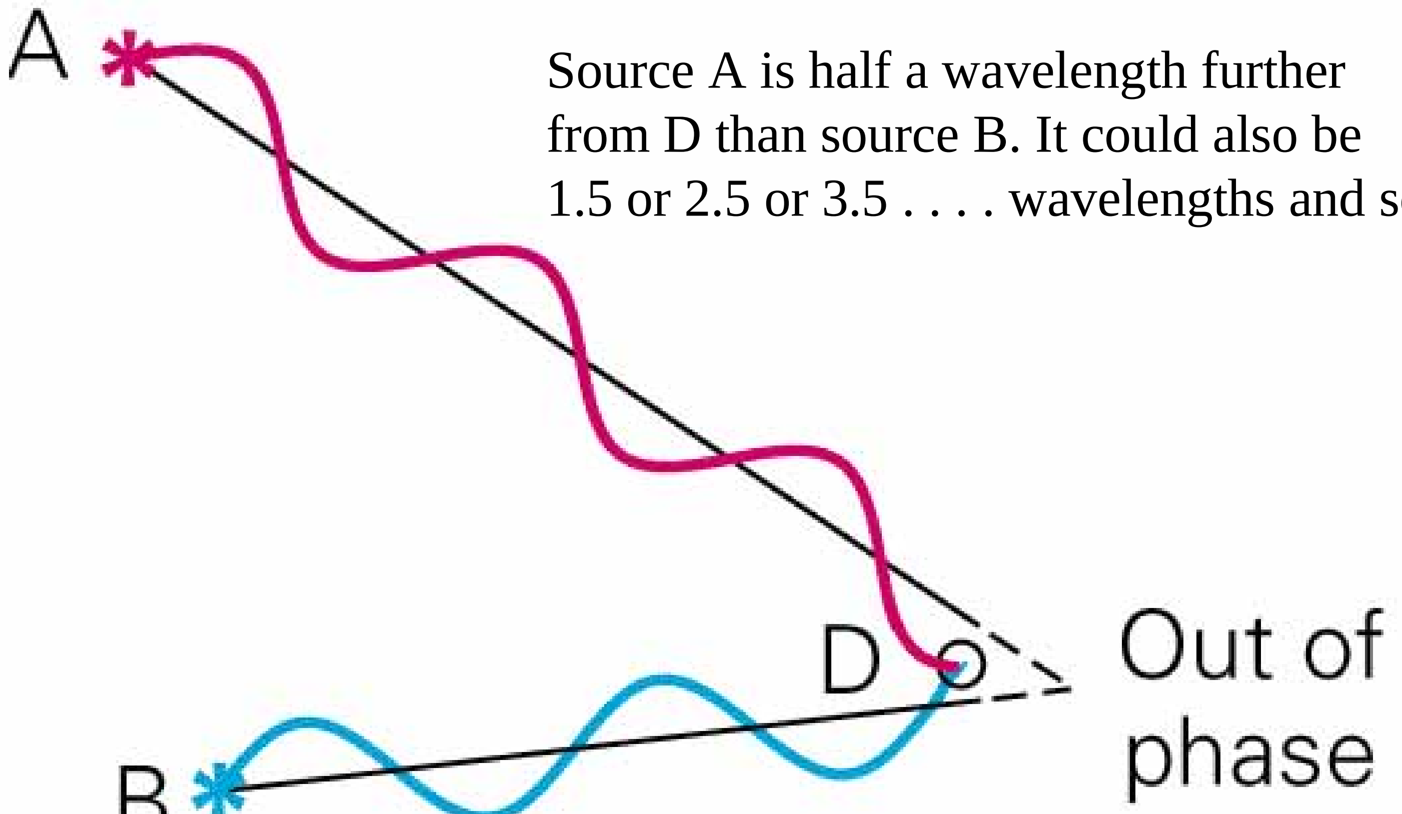
Source A is a whole number of wavelengths further from C than source B. It could be 1, 2, 3 . . . .whole wavelengths and so on.



(b)

The ONLY important quantity is the difference in the distance that the two waves travel to get to point C.

Waves can interfere destructively



Source A is half a wavelength further from D than source B. It could also be 1.5 or 2.5 or 3.5 . . . . wavelengths and so on.

(c)

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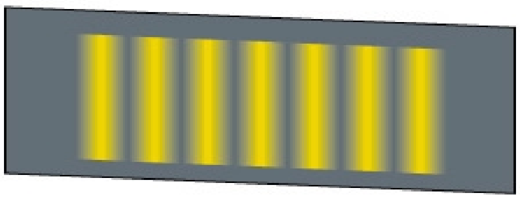
Young's double-slit experiment

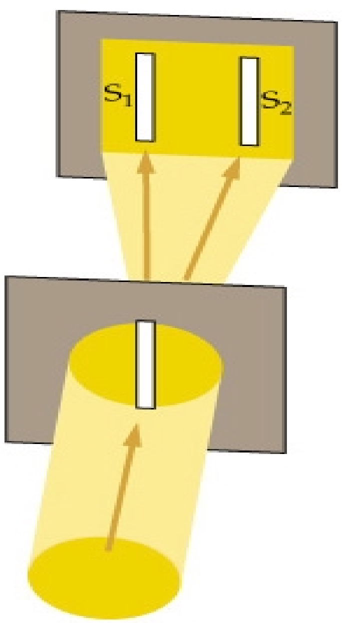
In Young's double-slit experiment, light passes through a pair of closely spaced narrow slits and produces a pattern of alternating bright and dark fringes on a view screen. The fringes arise because of constructive and destructive interference. The angle θ for *m*th higher-order bright fringe is given by

$\sin(\theta) = m\lambda/d$, where *d* is the spacing between the narrow slits, *lambda* is the wavelength of the light, and *m* = 0, 1, 2, 3, ... Similarly, the angle for the dark fringes is given by

$\sin(\theta) = (m + 1/2)\lambda/d$.

Figure 28–3 Young's two-slit experiment





- The first screen produces a small source of light that illuminates the two slits, S_1 and S_2. After passing through these slits the light spreads out into an interference pattern of alternating bright and dark fringes on a distant screen.

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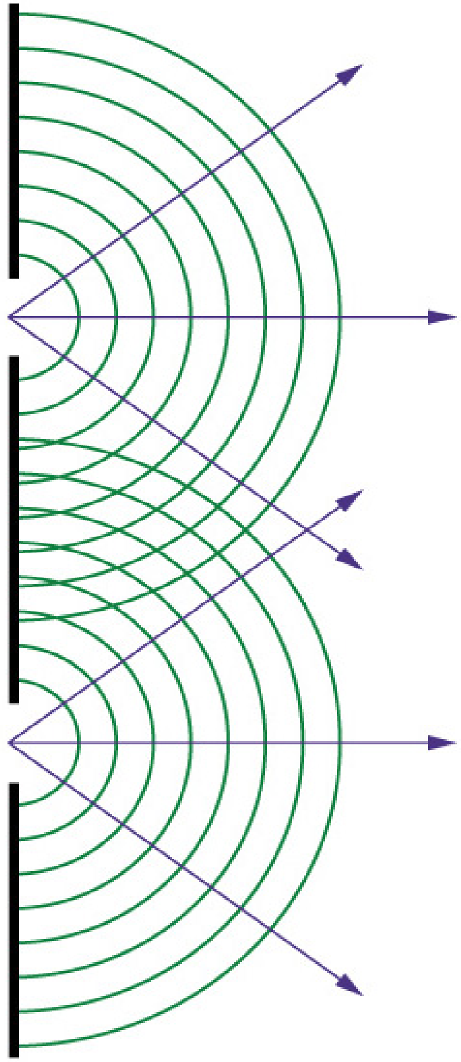
Huygens' principle

This principle states that every point on a wave front acts as a source of tiny wavelets that move forward with the same speed as the wave; the wave front at a later instant is the surface that is tangent to the wavelets.

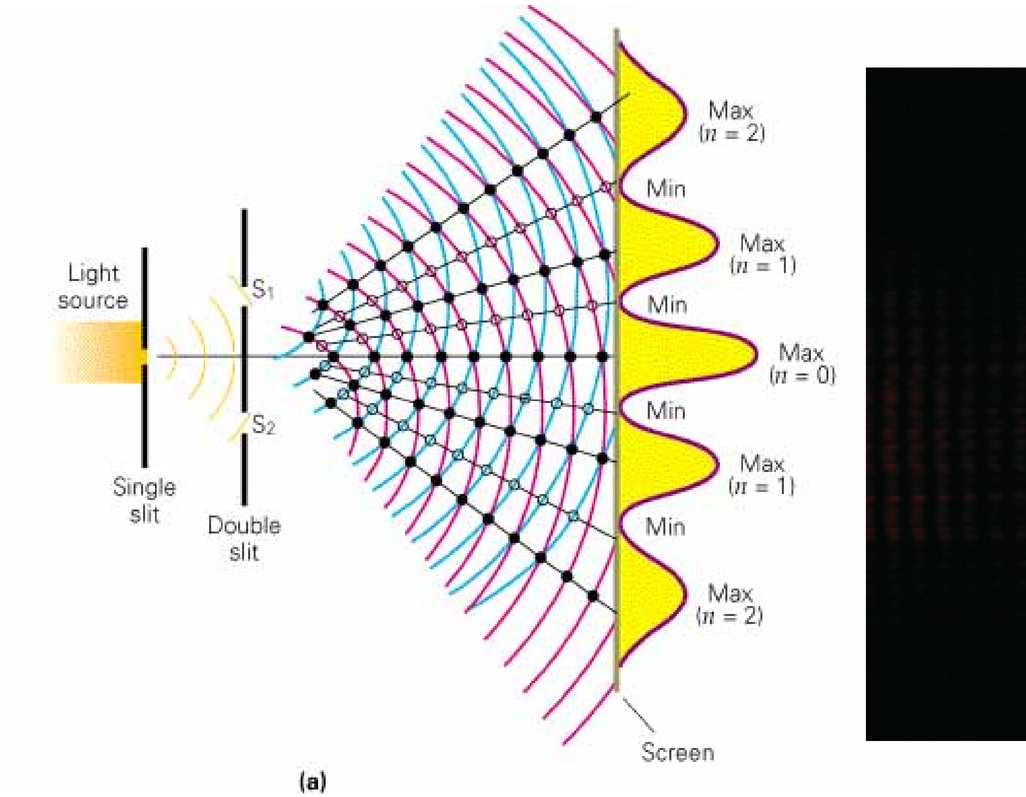
Figure 28–4 Huygen’s principle

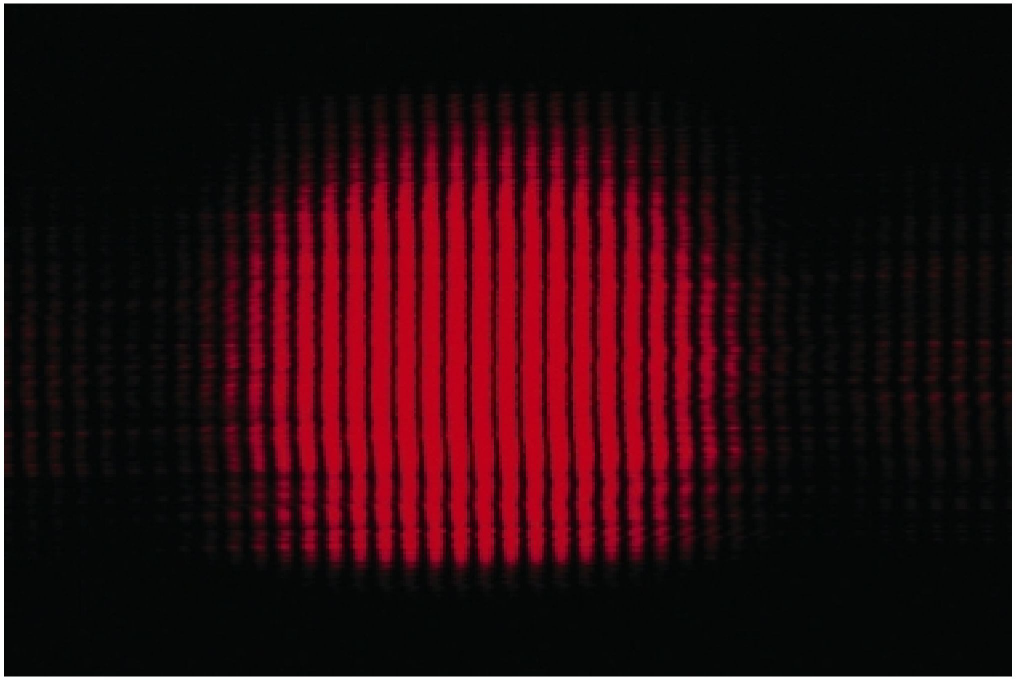


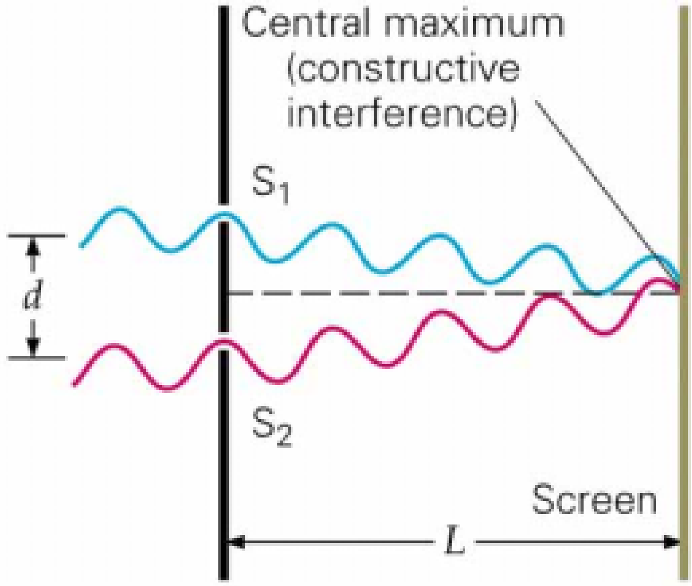
- According to Huygen’s principle, each of the two slits in Young’s experiment acts as a source of light waves propagating outward in all forward directions. It follows that light from the two sources can overlap, resulting in an interference pattern.

If light is a wave it should interfere constructively and destructively.

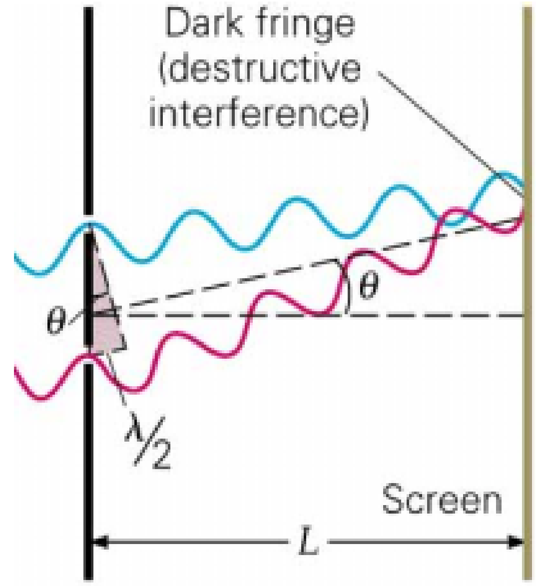
Young's Double Slit
Experiment



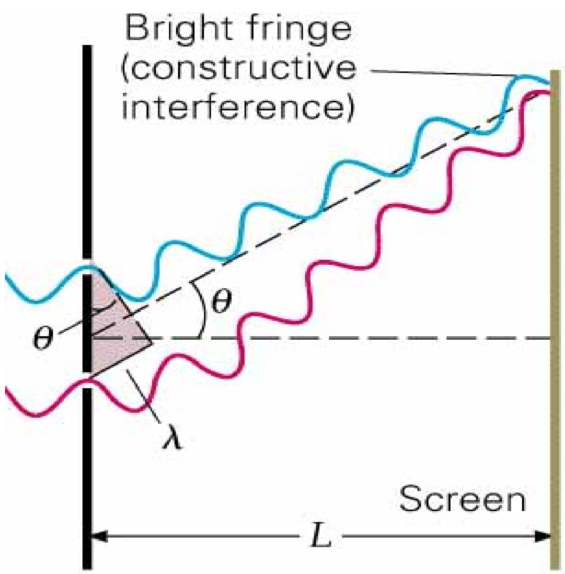



Central maximum
(constructive
interference)
S_1
d
S_2
Screen
L

(a)

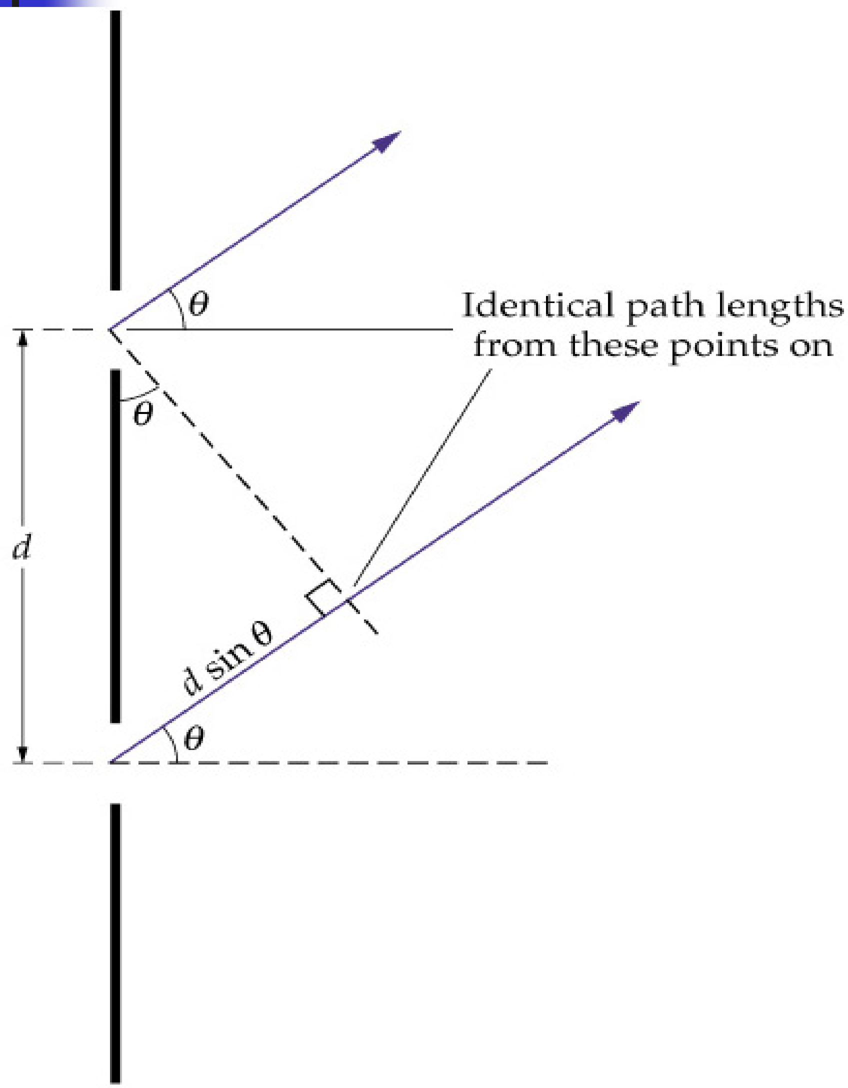

Dark fringe
(destructive
interference)
θ
θ
$\lambda/2$
Screen
L

(b)

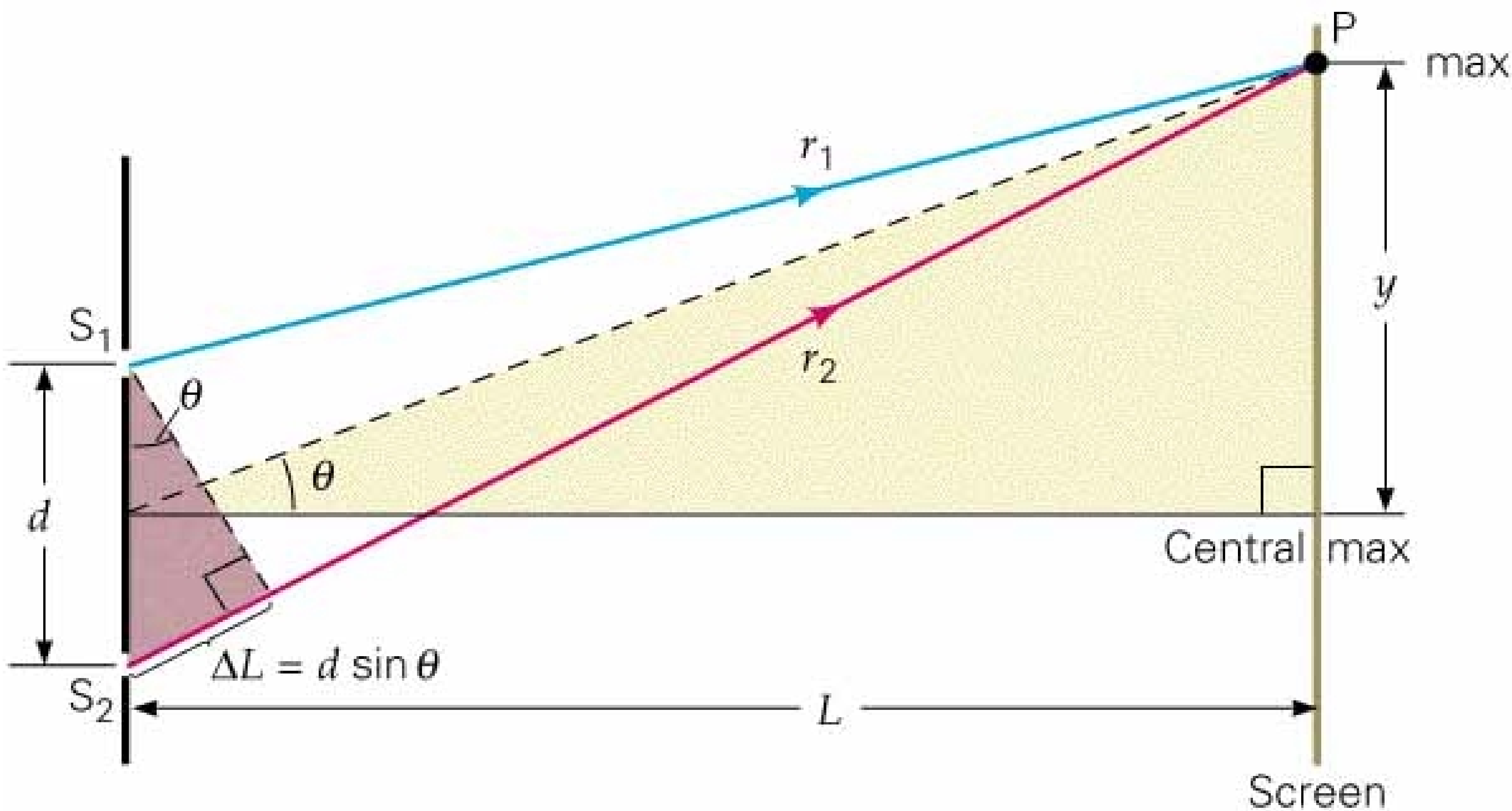

Bright fringe
(constructive
interference)
θ
θ
λ
Screen
L

(c)

Figure 28–5 Path difference in the two-slit experiment



- Light propagating from two slits to a distant screen along parallel paths; note that the paths make an angle q relative to the normal to the slits. The difference in path length is d sin q, where d is the slit separation.



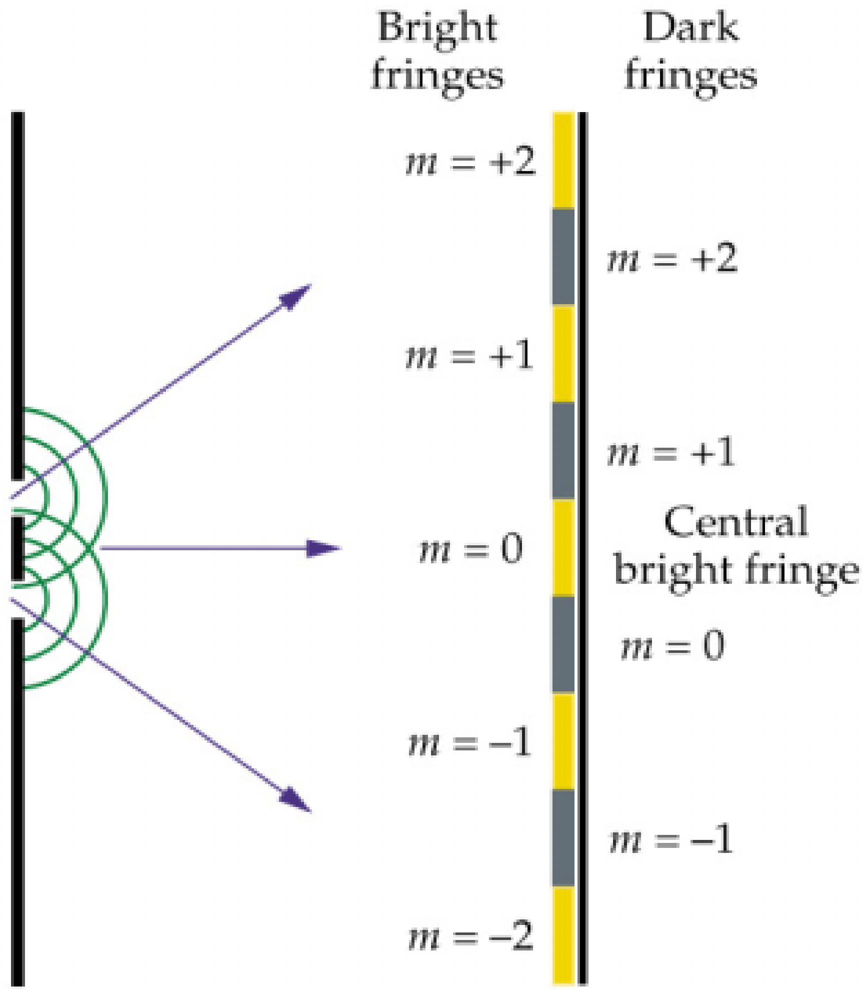
A **bright fringe** will occur at P whenever $\Delta L = m\lambda$

$\Delta L = m\lambda = d\sin\theta$ Bright fringe

$\Delta L = (m - 1/2)\lambda = d\sin\theta$ Dark fringe

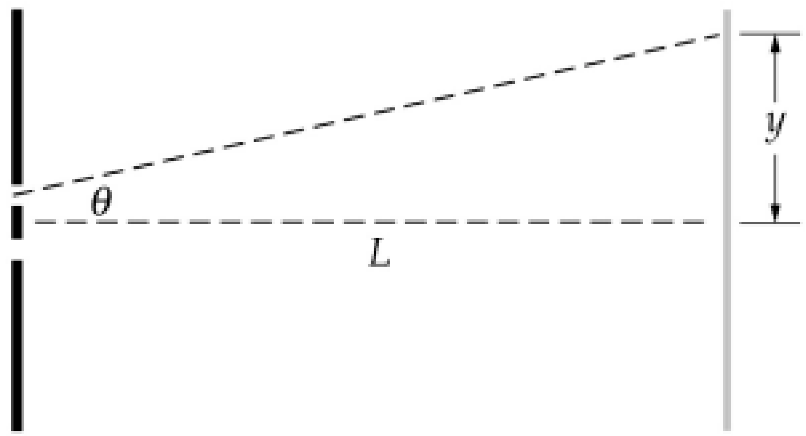
$m = 0, +/-1, +/-2 \ldots$

Figure 28–6 The two-slit pattern



- Numbering systems for bright and dark fringes.

Figure 28–7 Linear distance in an interference pattern



- If light propagates at an angle η relative to the normal to the slits, it is displaced a linear distance y = L tan η on the distant screen.

$$y = L\tan\theta$$

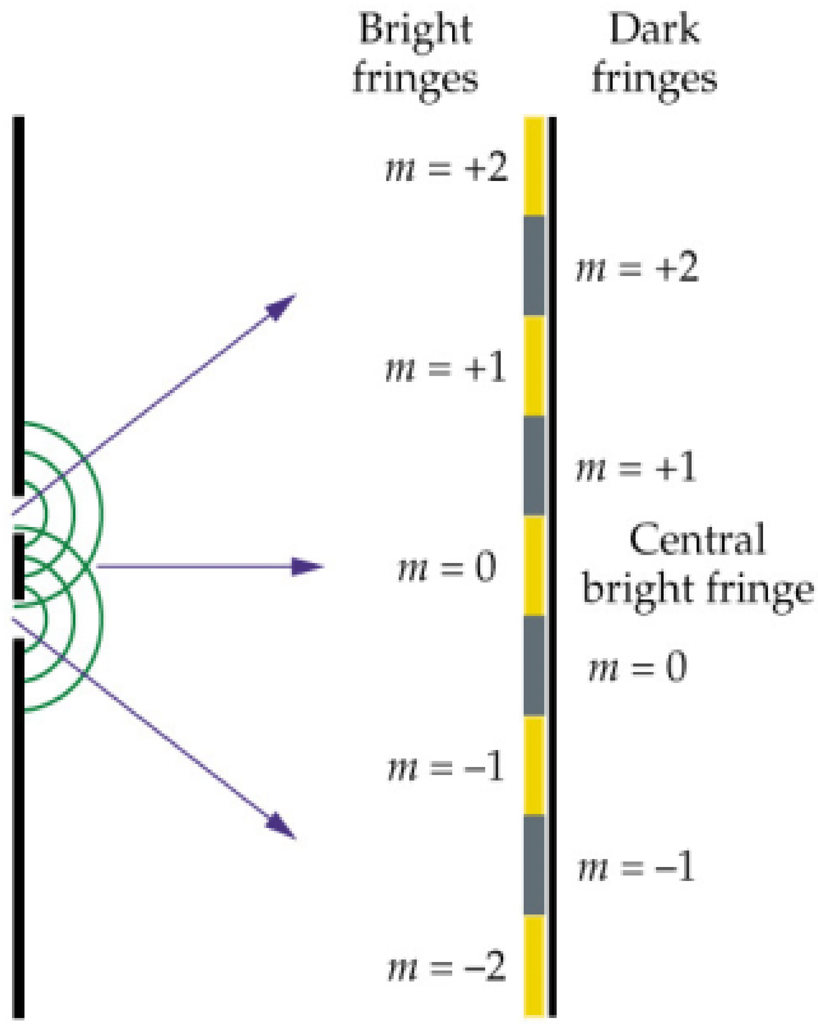
If d << L then $\tan\theta = \sin\theta = \theta$

ANGLE IS IN RADIANS

$$y = L\theta$$

$$\Delta L = d\sin\theta = d\frac{y}{L} = n\lambda$$

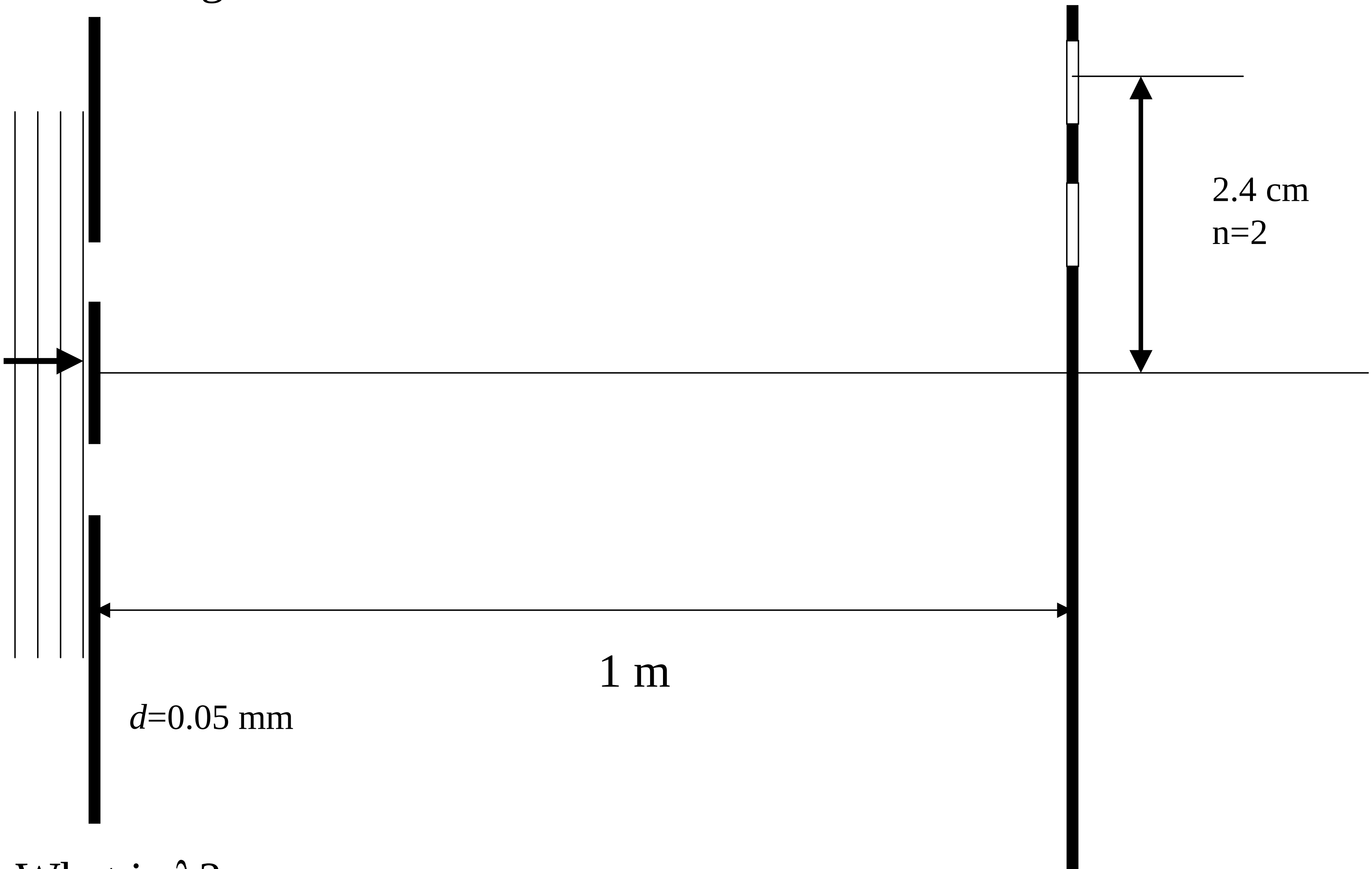
for a bright fringe (constructive interference)



$$\lambda = \frac{y_n d}{nL}$$

The wavelength of light can be calculated. This was what Thomas Young did.

Young's Slit Problem



What is λ?

What if blue light (λ =400 nm) were used?

$$\lambda = \frac{y_n d}{nL} = \frac{(0.024m)(0.05x10^{-3}m)}{2(1)} = 6x10^{-7}m = 600nm$$

$$y_n = \frac{\lambda nL}{d} = \frac{(2)(4x10^{-7}m)(1m)}{0.05x10^{-3}m} = 16mm$$

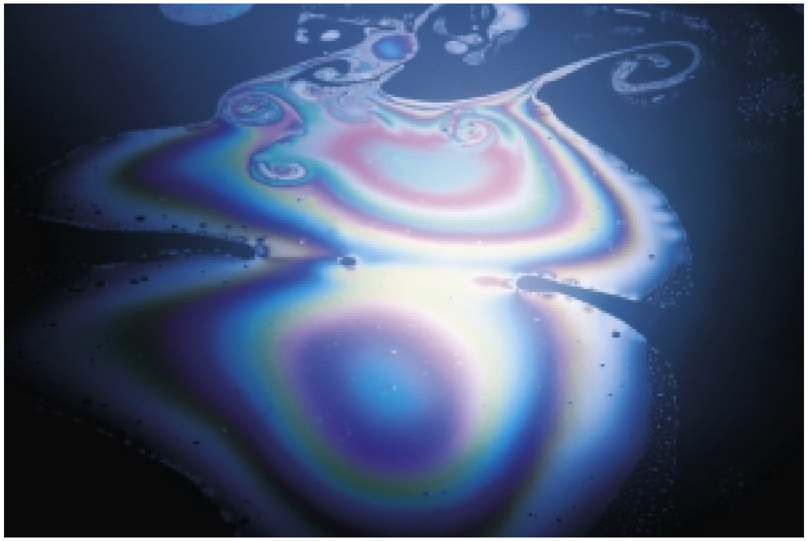
If white light were shined on the slits then the colors would separate for each bright fringe. Blue being closest to the axis red being furthest away.

Thin Film Interference: Interference in reflected light.

Soap bubbles and oil slicks.

Why do soap bubbles display all types of colors?

Same with oil films on water etc?



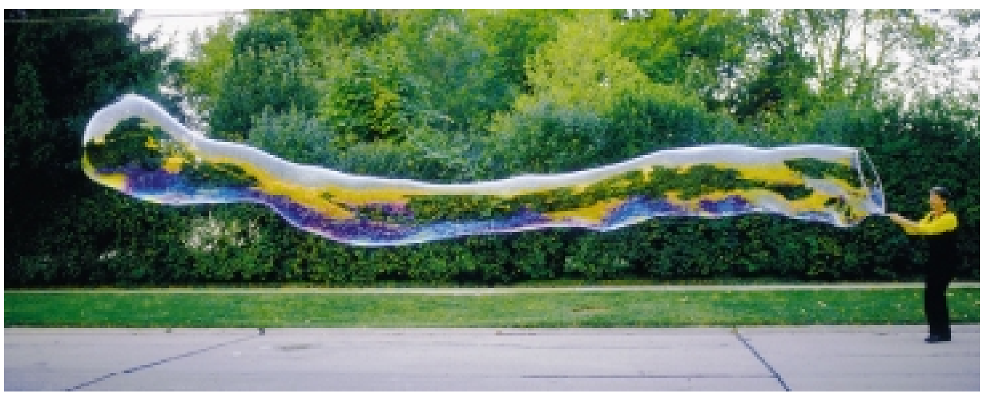
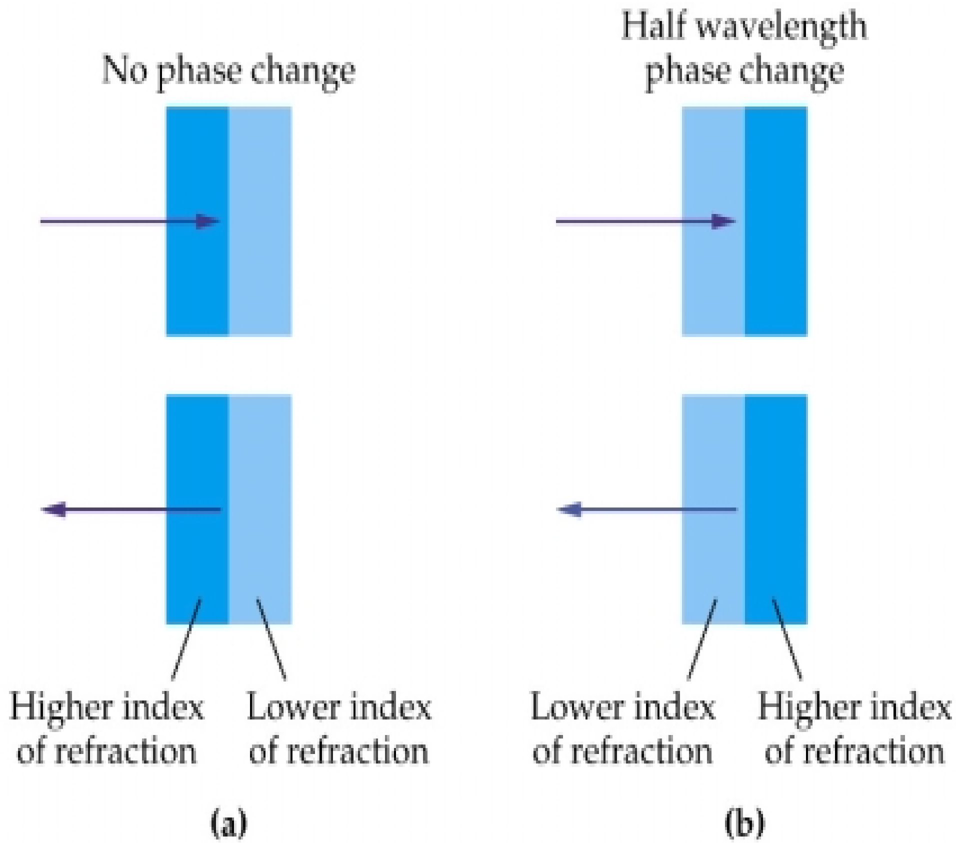
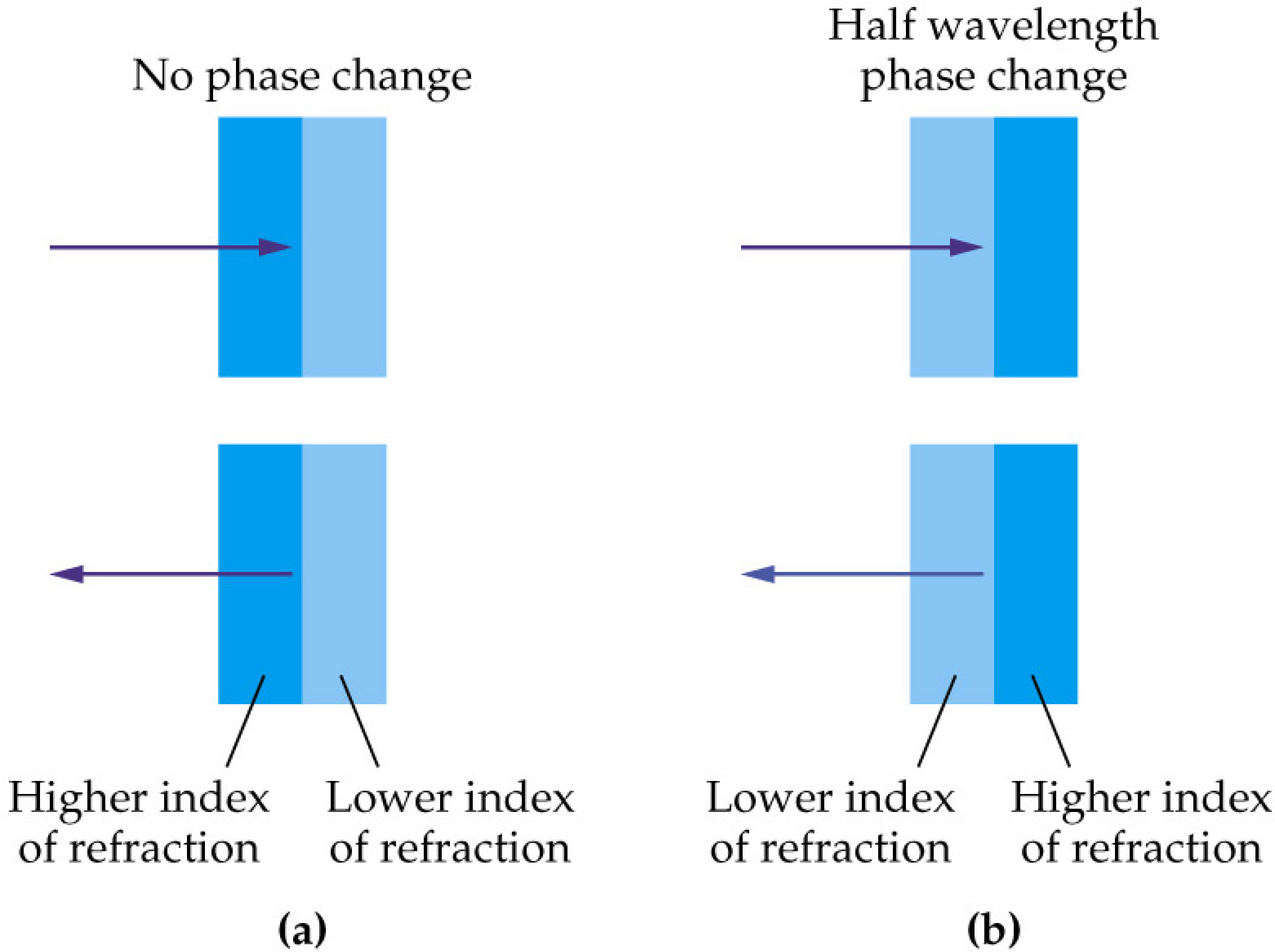


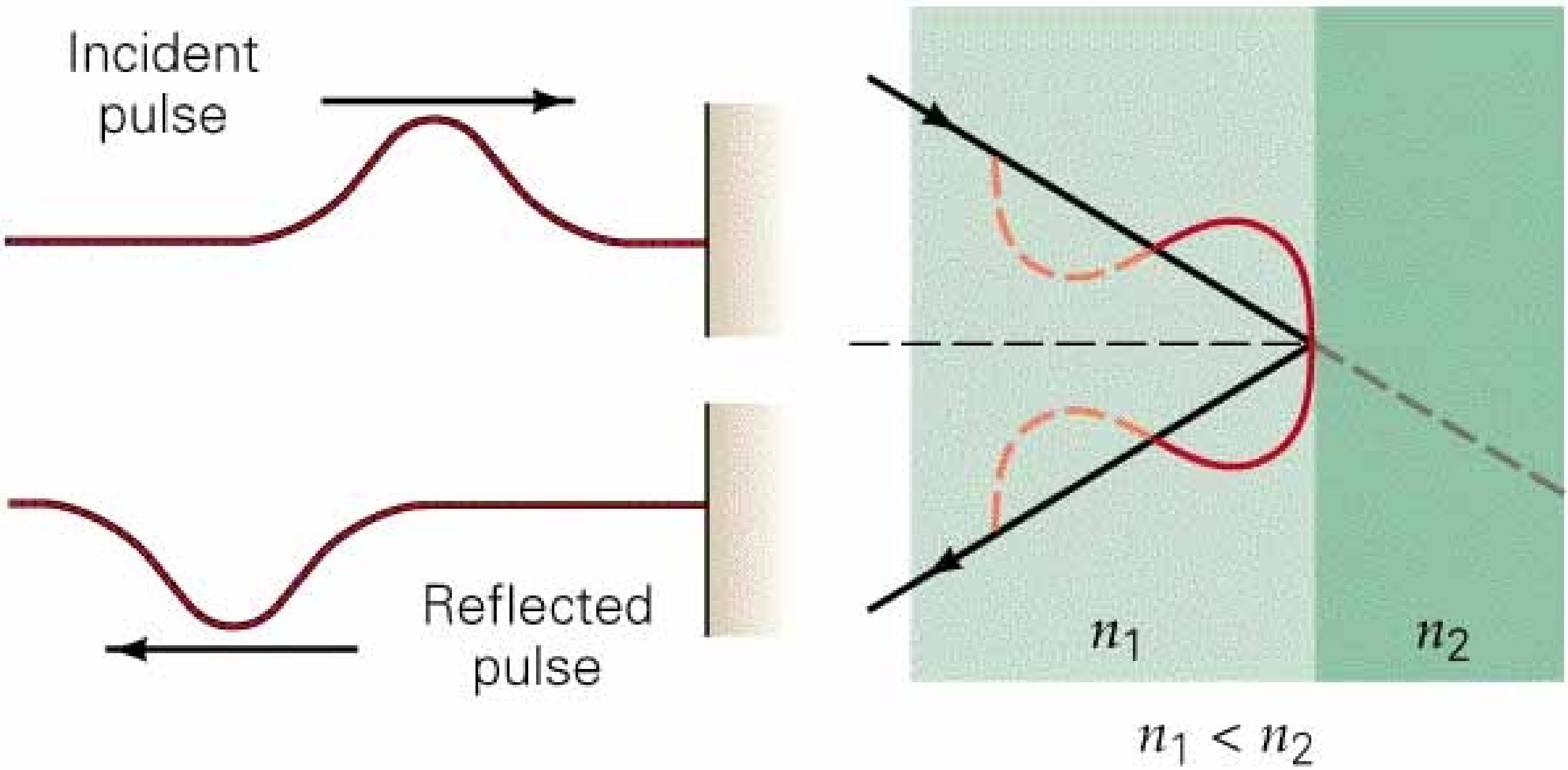
Figure 28–8 Phase change with reflection



- (a) An electromagnetic wave reflects with no phase change when it encounters a medium with a lower index of refraction. (b) An electromagnetic wave reflects with a half-wavelength (180°) phase change when it encounters a medium with a larger index of refraction.

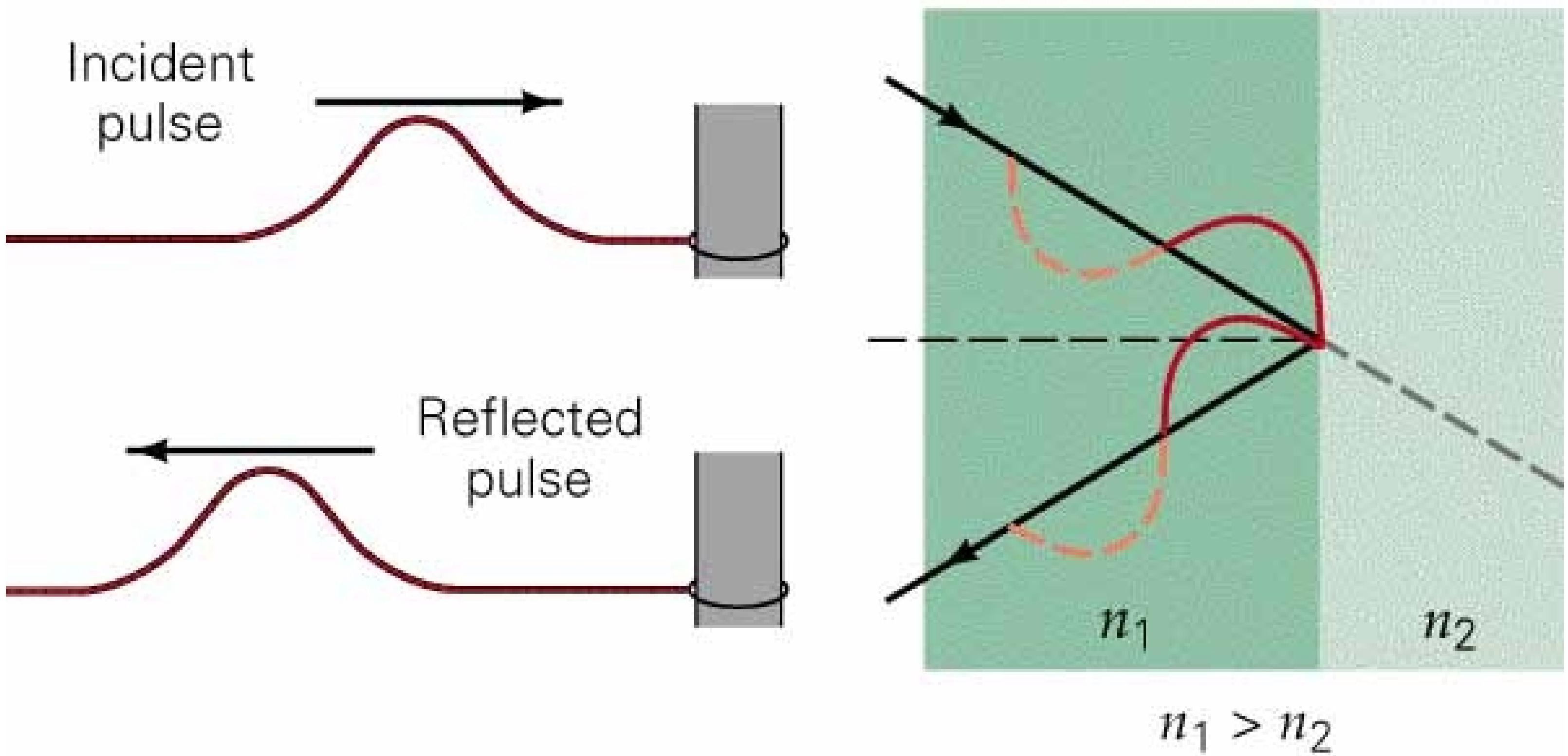

No phase change
Half wavelength phase change
Higher index of refraction
Lower index of refraction
Lower index of refraction
Higher index of refraction
(a)
(b)

Light reflected from a more dense medium changes phase by ½ wavelength or 180 degrees.



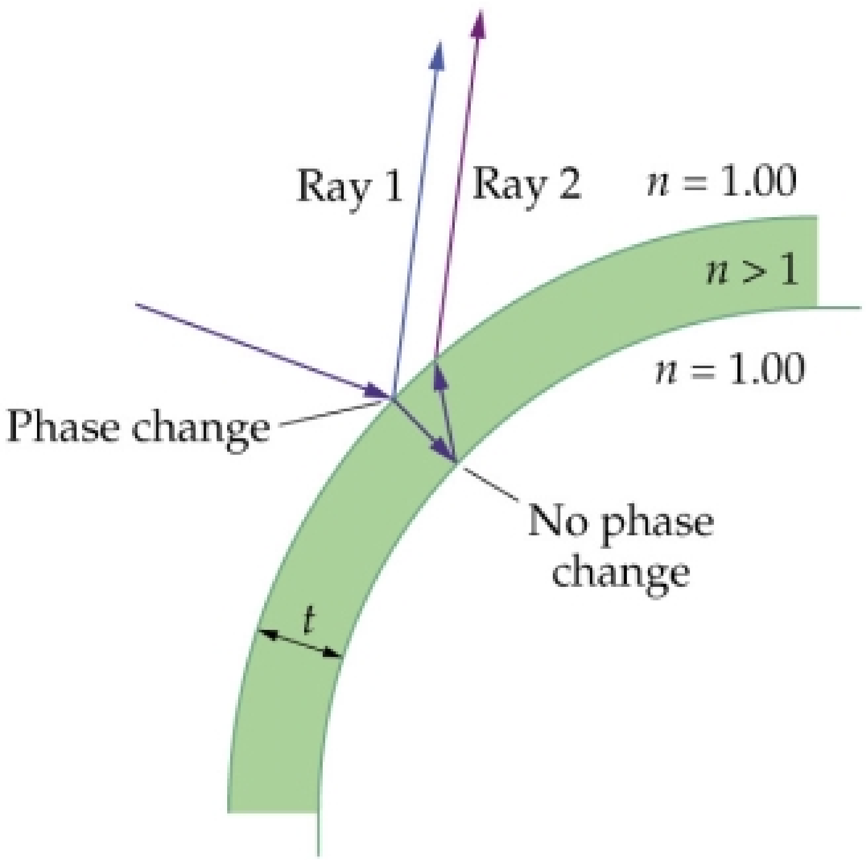
(a) Fixed end: 180° phase shift

$n_2 > n_1$



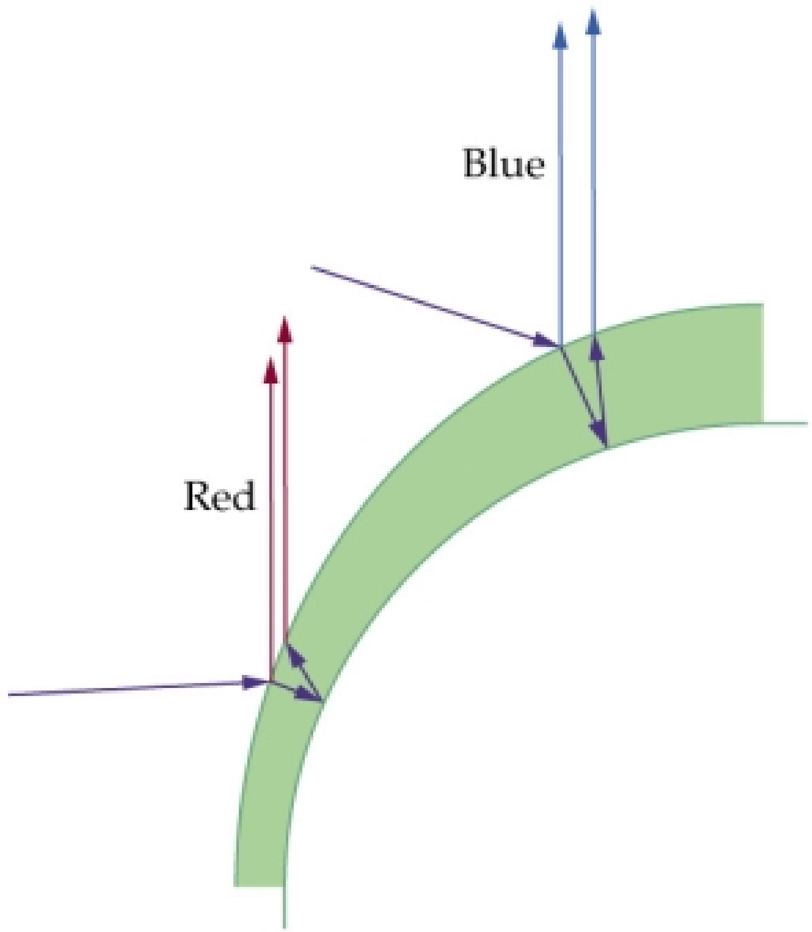
(b) Free end: zero phase shift

Figure 28–12 Interference in thin films



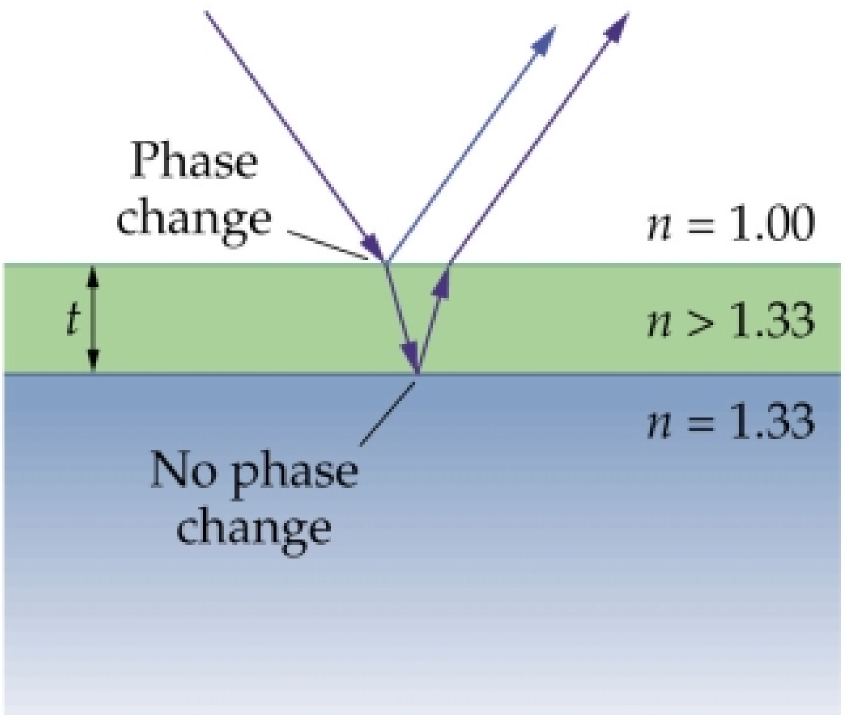
- The phase of ray 1 changes by half a wavelength due to reflection; the phase of ray 2 changes by $2t / \kappa_n$ where κ_n is the wavelength of light within the thin film.

Figure 28–13 Thickness and color in a thin film

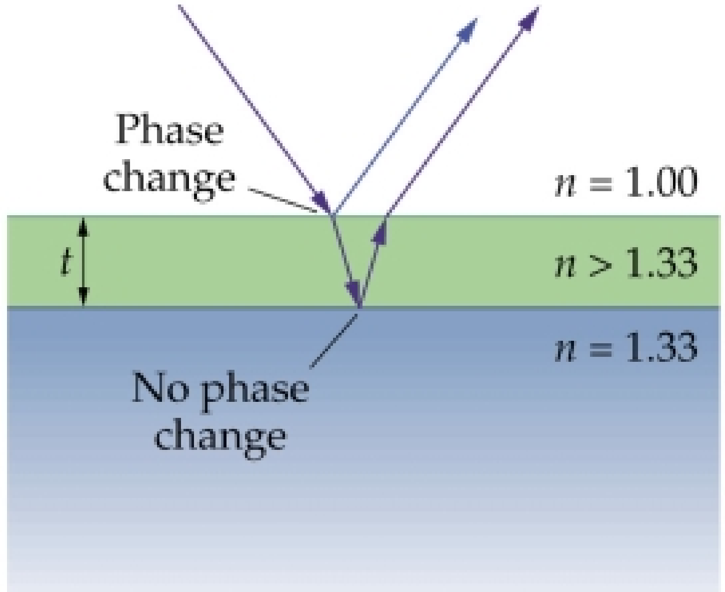


- Thicker portions of thin film appear blue, since the long-wavelength red light experiences destructive interference. Thinner regions appear red because the short-wavelength blue light interferes destructively.

Figure 28–14 A thin film with one phase change



- If the index of refraction of the film is greater than that of the water, the situation in terms of phase changes is essentially the same as for a thin film suspended in air.



Oil on water: Beams 1 and 2 would have interfered constructively when:

$$\mathbf{2}\boldsymbol{t} = \mathbf{m}\boldsymbol{\lambda}_{\mathbf{f}} = \mathbf{m}\boldsymbol{\lambda}_{\mathbf{A}} \,/\, \mathbf{n}, \qquad \mathbf{m=1, 2, 3 \ldots}$$

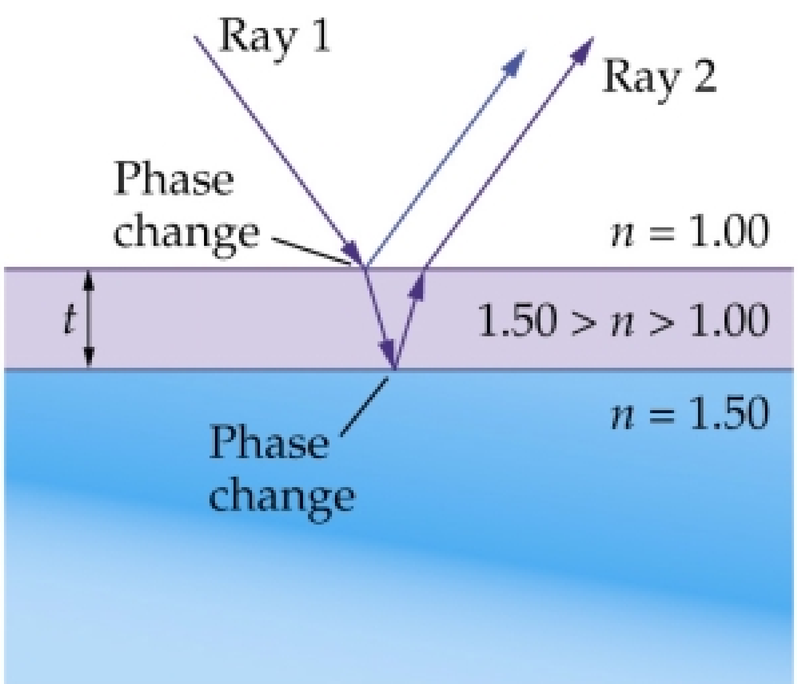
BUT beam 1 undergoes a half wavelength phase shift. So when

$$\mathbf{2}\boldsymbol{t} = \mathbf{m}\boldsymbol{\lambda}_{\mathbf{A}} \,/\, \mathbf{n}$$ **The two beams interfere destructively**

The minimum thickness for destructive interference is $\boldsymbol{t} = \boldsymbol{\lambda}_{\mathbf{A}} \,/\, \mathbf{2n}$

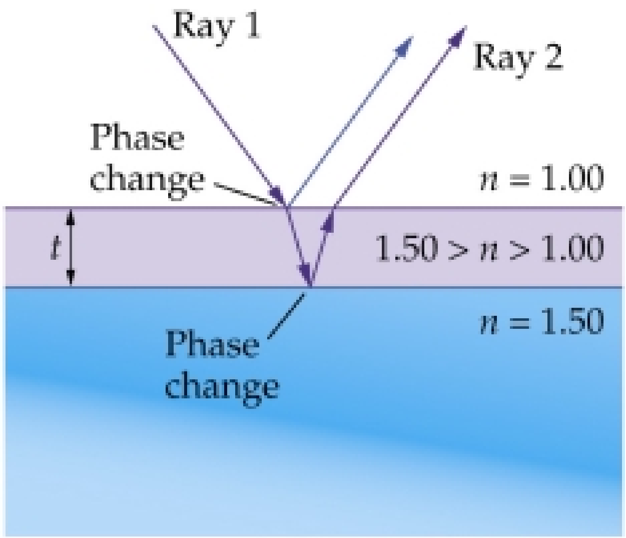
What this means is that no light will be reflected from the surface.
All the light will be transmitted and you will not see the film.

Figure 28–15 A thin film with two phase changes



- A thin film is applied to a material with a relatively large index of refraction. If the index of refraction of the film is less than that of the material that supports it, there will be a phase change for reflections from both surfaces of the film. Films of this type are often used in nonreflective coatings.

Let's say we replaced the water with a piece of glass with refractive index = 1.7. That is, the film is now on the glass.



Light beams 1 and 2 both undergo a phase change.
So both beams interfere constructively when

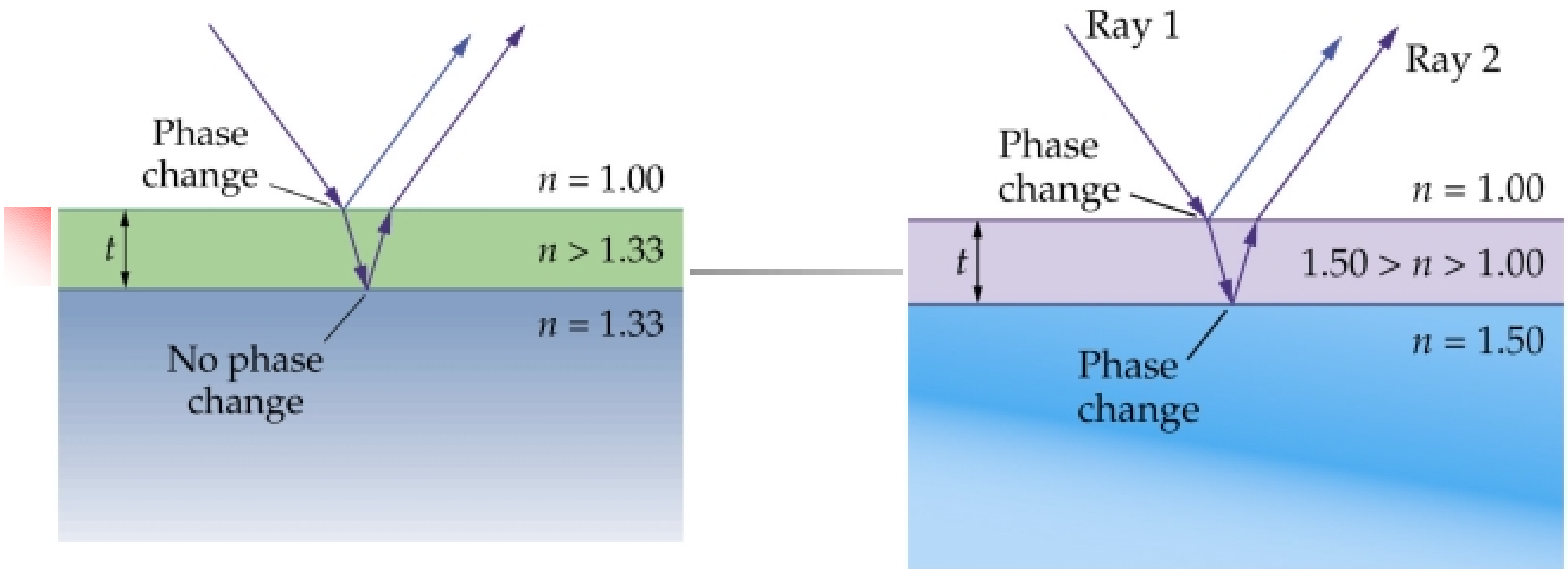
$$\mathbf{2\boldsymbol{t} = m\lambda_f = m\lambda_A / n, \qquad m=1, 2, \ldots}$$

and destructively when

$$\mathbf{2\boldsymbol{t} = (m+½)\ \lambda_f = (m+½)\ \lambda_A / n, \qquad m=0, 1, 2 \ldots}$$

Minimum thickness, m=0: $t = ¼\ \lambda_f$

When both beams interfere constructively what you will see is a bright colored film on the surface.



In both examples beams 1 and 2 will interfere. How they interfere depends on by how much beam 2 is moved relative to beam 1. This depends on the thickness, t.

A thin layer of oil (n=1.5) floats on water. Destructive interference is observed for 480 and 600 nm light at different locations on the film. Find the two Minimum thicknesses of the film at the two locations.

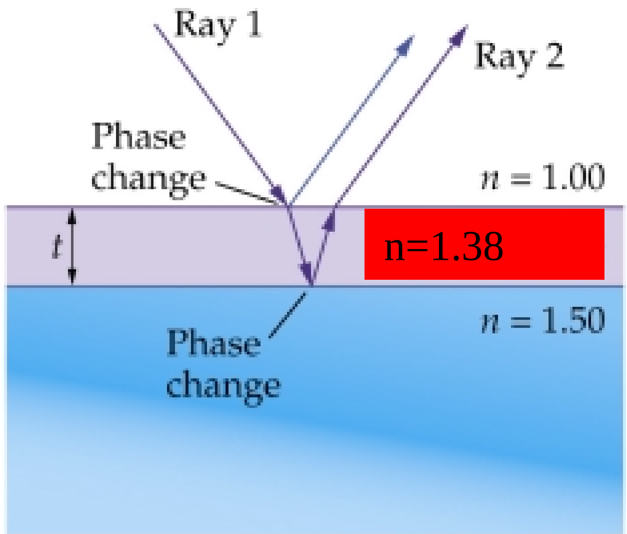
Solution: The first reflection has 180° phase shift. So the condition for destructive interference becomes

$$\Delta L = 2t = \lambda_n, \text{ where } \lambda_n = \frac{\lambda}{n}. \quad \text{So} \quad t = \frac{\lambda}{2n}.$$

$$\text{Therefore} \quad t_1 = \frac{480\text{ nm}}{2(1.5)} = \boxed{160\text{ nm}} \quad \text{and} \quad t_2 = \frac{600\text{ nm}}{2(1.5)} = \boxed{200\text{ nm}}.$$

Anti reflection coatings on optical instruments. MgF_2

Red light (670 nm) interferes destructively upon reflection



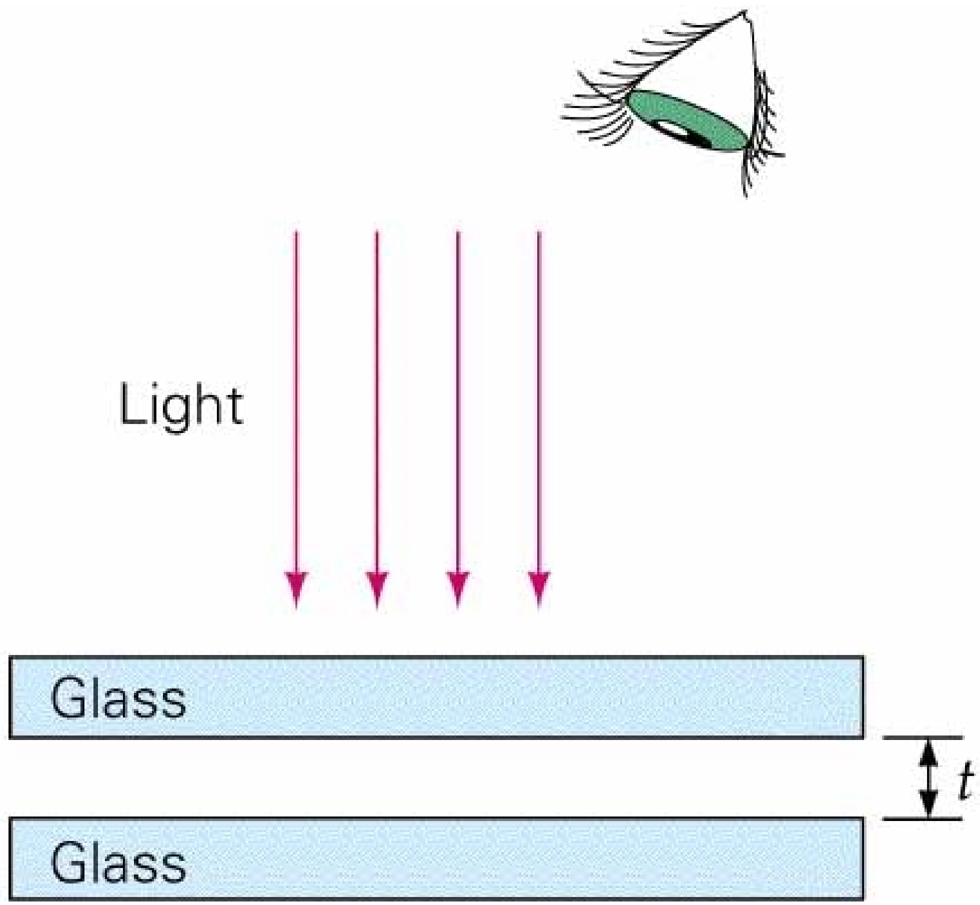
Light beams 1 and 2 undergo a phase change. So both beams interfere destructively when

$$\mathbf{2\mathit{t} = (m\text{-}½)\ \lambda_A / n}$$

Minimum thickness:

$$\mathbf{\mathit{t} = ¼\lambda_A / n}$$

Two parallel glass plates are separated by a small distance, t, as shown. If the top plate is illuminated with light from a helium neon laser (λ = 632.8 nm), for what minimum separation distances will the light be (A) reflected from the air interface to the observer (B) Transmitted through the plates? Note: zero is not an answer.



Solution:

(a) The two rays for interference are the reflections from the bottom surface of the top plate and the top surface from the bottom plate. The reflection from the top surface of the bottom plate has 180° phase shifts, so the condition for constructive interference for reflection is

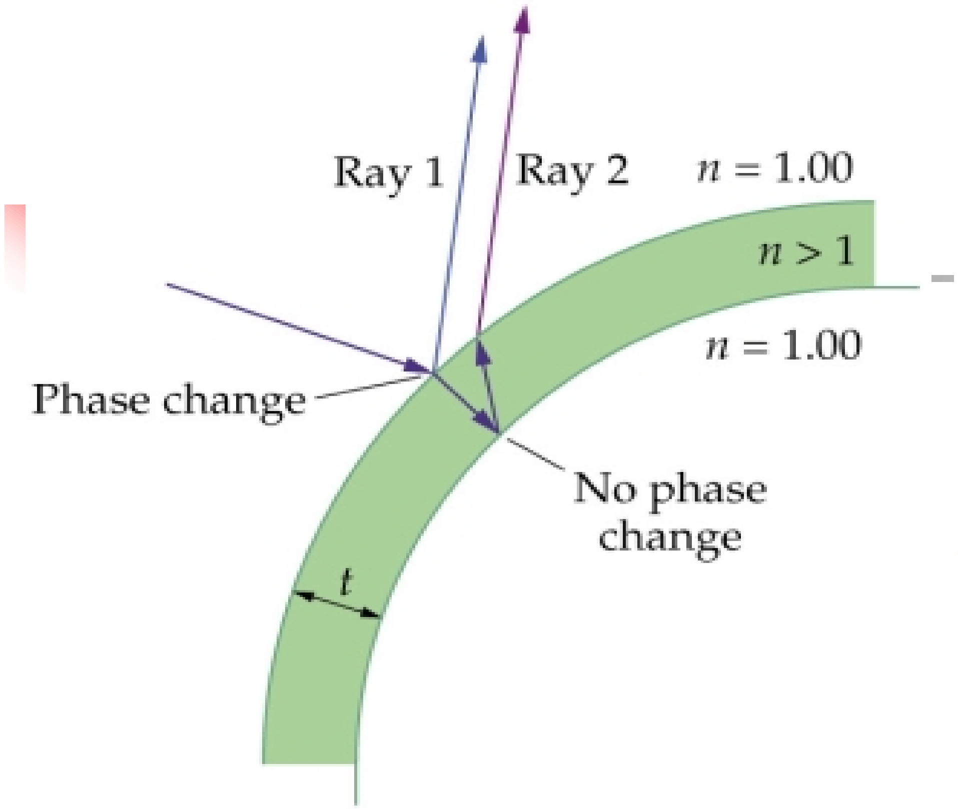
$$\Delta L = 2t = \frac{\lambda}{2},$$

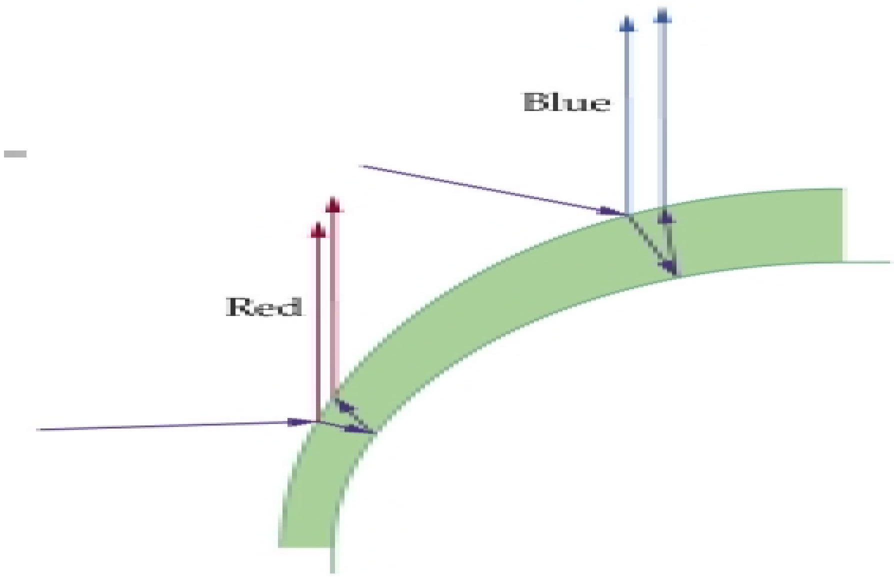
so $$t = \frac{\lambda}{4} = \frac{632.8 \text{ nm}}{4} = \boxed{158.2 \text{ nm}}.$$

(b) Constructive for transmission is the same as destructive for reflection.

So $\Delta L = 2t = \lambda,$ ☞ $t = \dfrac{\lambda}{2} = \dfrac{632.8 \text{ nm}}{2} = \boxed{316.4 \text{ nm}}.$

Soap Films. Film has air on either side.





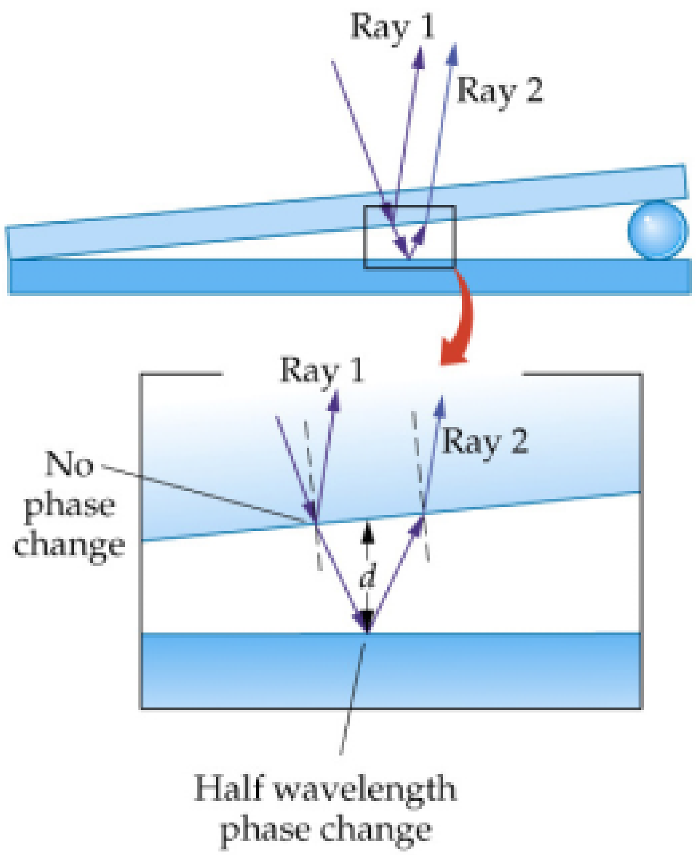
Light beams 1 undergo a phase change. So both beams interfere destructively when

$$\mathbf{2}\boldsymbol{t} = \mathbf{m}\boldsymbol{\lambda}_{\mathbf{f}} = \boldsymbol{\lambda}_{\mathbf{A}} \,/\, \mathbf{n}, \qquad \mathbf{m=1, 2, \ldots.}$$

and constructively when

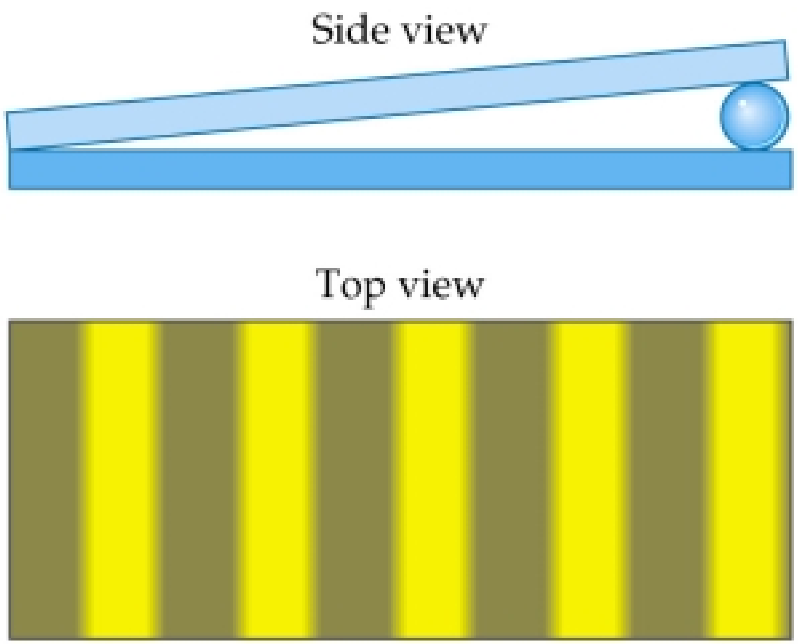
$$\mathbf{2}\boldsymbol{t} = \mathbf{(m\text{-}½)}\, \boldsymbol{\lambda}_{\mathbf{f}} = \mathbf{(m\text{-}½)}\, \boldsymbol{\lambda}_{\mathbf{A}} \,/\, \mathbf{n}, \qquad \mathbf{m=0, 1, 2 \ldots.}$$

Figure 28–9 An air wedge



- In an air wedge, interference occurs between the light reflected from the bottom surface of the top plate of glass (ray 1) and light reflected from the top surface of the bottom plate of glass (ray 2).

Figure 28–10 Interference fringes in an air wedge



- The interference fringes in an air wedge are regularly spaced, as shown in the top view of the wedge.

Figure 28–11 A system for generating Newton's rings

- (a) A variation on the air wedge is produced by placing a piece of glass with a spherical cross section on top of a plate of glass. (b) A top view of the system shown in part (a). The circular interference fringes are referred to as Newton's rings. Here again, the radiation used is monochromatic light—in this case from sodium atoms.

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Diffraction

Diffraction is a bending of waves around obstacles or the edges of an opening. Diffraction is an interference effect that can be explained with the aid of *Huygens' principle*.

Diffraction:

Water waves diffract. Sound waves diffract.

Why can you hear me from around a doorway but you cannot see me?

Diffraction manifests itself in the apparent bending of waves around small obstacles and the spreading out of waves past small openings.

The amount of bending depends on the width of the aperture that the wave moves through **and** the wavelength of the wave:

$$\sin\theta \propto \lambda / w$$

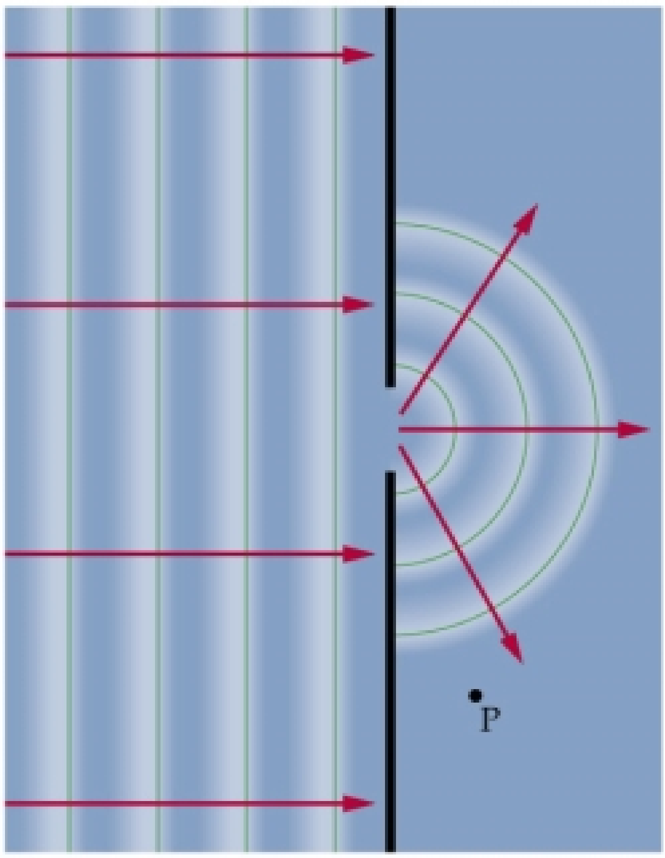
Sound waves have wavelengths similar to the width of a doorway so the amount of diffraction (bending is large).

Light waves have wavelengths much much less than the width of a

doorway so the amount of diffraction (bending) is very small.

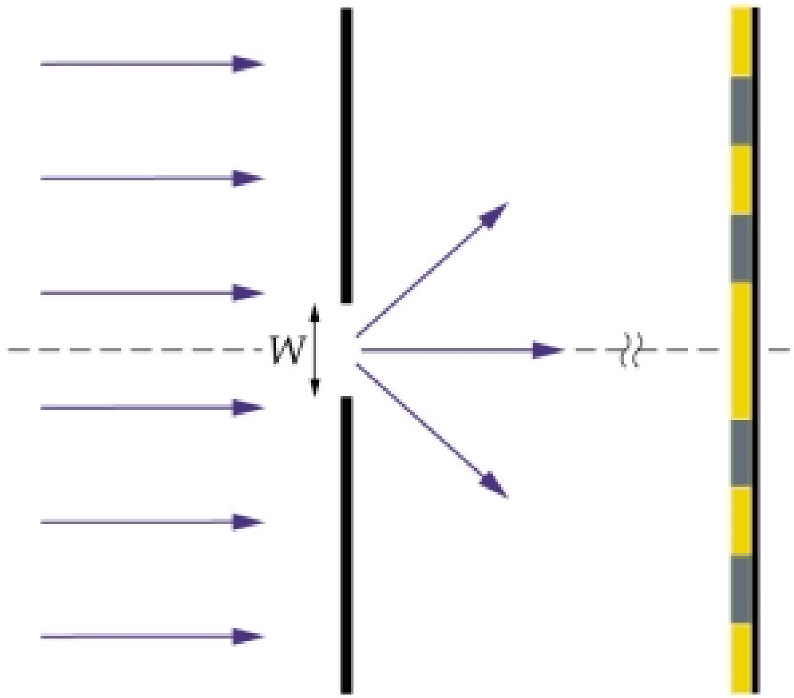
If you have an aperture that is close to the wavelength of light (say 500 nm) then the amount of bending is large.

Figure 28–17 Diffraction of water waves



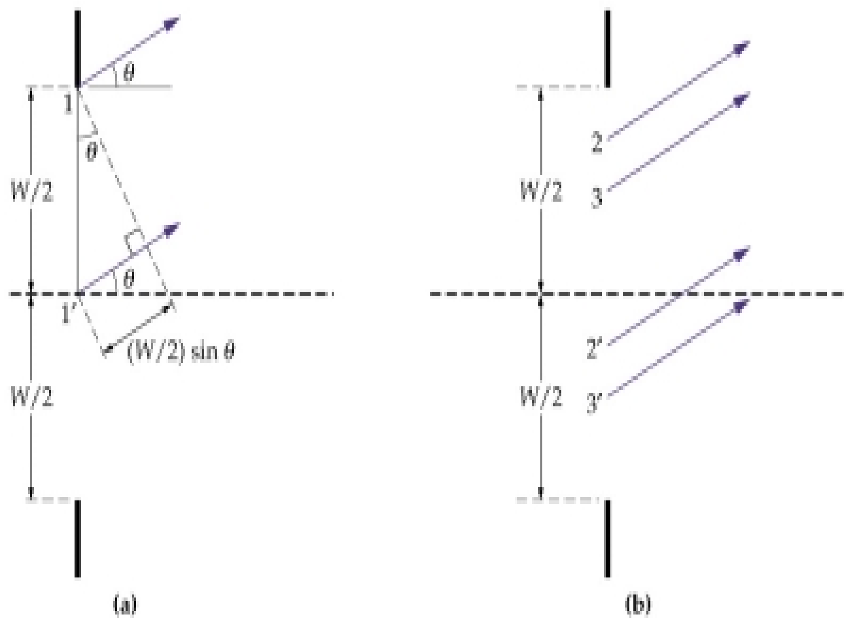
- As water waves pass through an opening they diffract, or change direction. Thus, an observer at point P detects waves, even though this point is not on a line with the original direction of the waves and the opening. All waves exhibit similar diffraction behavior.

Figure 28–18 Single-slit diffraction

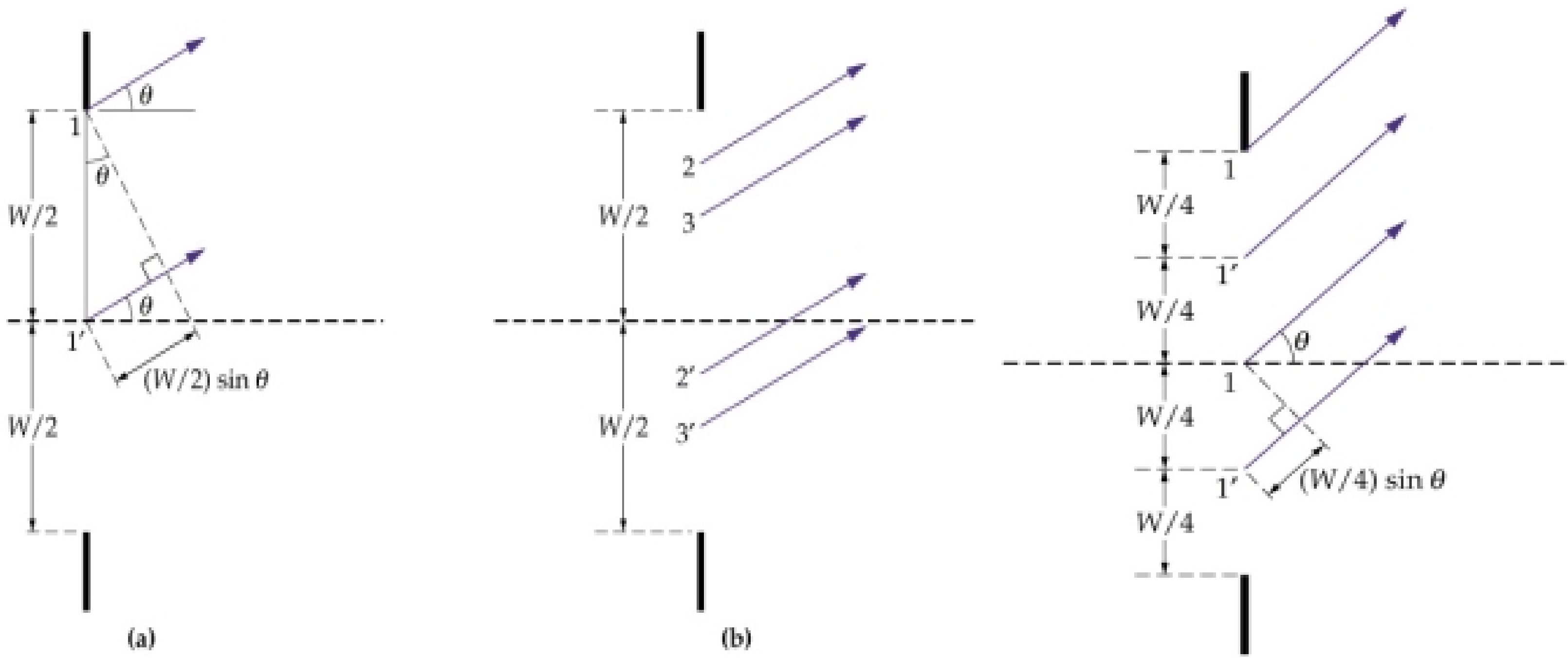


- When light of wavelength l passes through a slit of width W a “diffraction pattern” of bright and dark fringes is formed.

Figure 28–19 Locating the first dark fringe in single-slit diffraction



The location of the first dark fringe in single-slit diffraction can be determined by considering pairs of waves radiating from the top and bottom half of a slit. (a) A wave pair originating at points 1 and 1' has a path difference of (W/2) sinη. These waves interfere destructively if the path difference is equal to half a wavelength. (b) The rest of the light coming from the slit can be considered to consist of additional wave pairs, like 2 and 2', 3 and 3', and so on. Each wave pair has the same path difference.

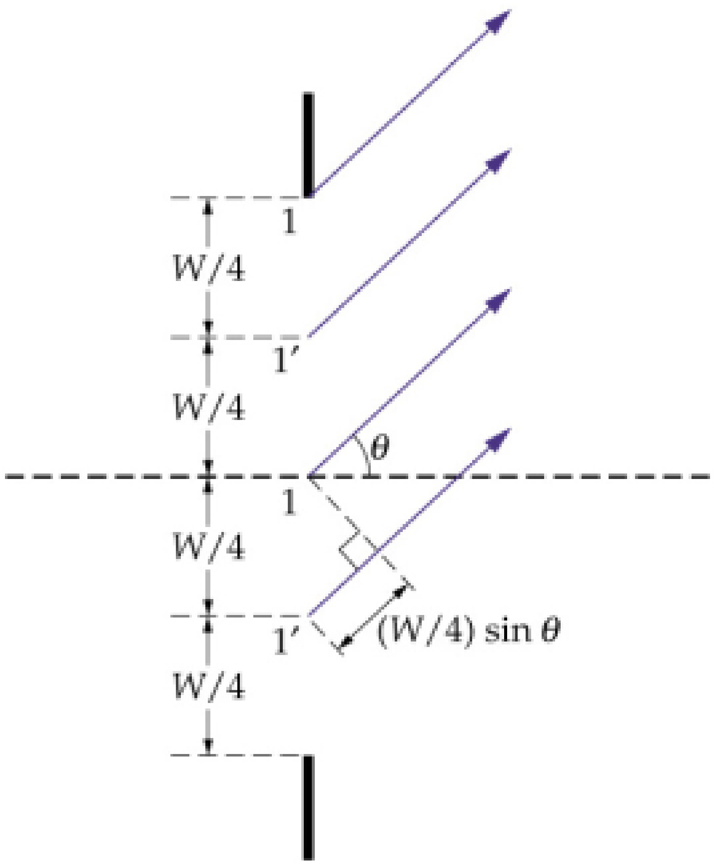


The **dark fringes** occur when

$$\boldsymbol{W/2 \sin\theta = m\,\lambda / 2,} \qquad \textbf{m=1,2,3…….}$$

$$\boldsymbol{W \sin\theta = m\,\lambda,} \qquad \textbf{m=+/-1, +/-2, +/-3…….}$$

Figure 28–20 Locating the second dark fringe in single-slit diffraction

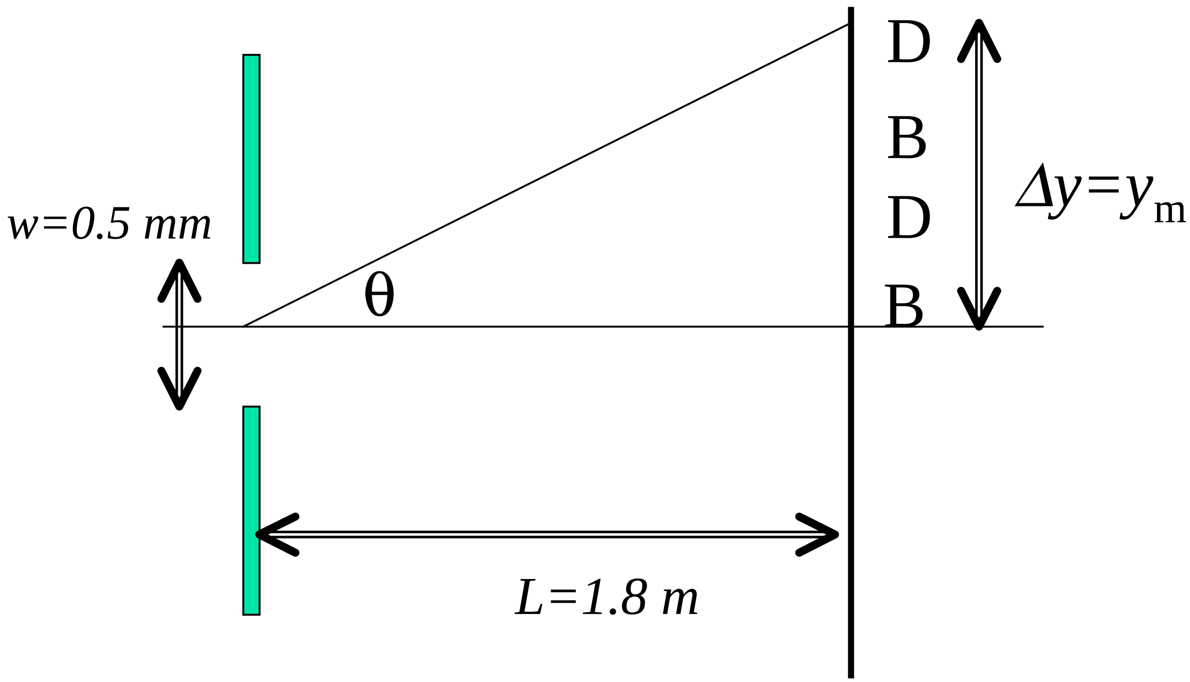


- To find the second dark fringe in a single-slit diffraction pattern, we divide the slit into four regions and consider wave pairs that originate from points separated by a distance W/4. Destructive interference occurs when the path difference, (W/4) sin q, is half a wavelength.

Problem 42: A single slit of width 0.5 mm is illuminated with monochromatic light (λ=680 nm). A screen is placed 1.8 m from the slit to observe the fringe pattern.

(A) What is the angle between the second dark fringe (m=2) and the central maximum?

(B) What is the lateral displacement of this dark fringe?



a) $w \sin\theta = m\lambda$, ☞ $\theta = \sin^{-1}\dfrac{m\lambda}{w} = \sin^{-1}\dfrac{(2)(680\times 10^{-9}\text{ m})}{0.50\times 10^{-3}\text{ m}} = \boxed{0.16^\circ = 2.7\times 10^{-3}\text{ rad}}$.

(b) $\Delta y = \theta L = (2.72\times 10^{-3}\text{ rad})(1.80\text{ m}) = \boxed{4.9\text{ mm}}$.