

Interference of Light Waves: Young's Double-Slit Experiment

At the end of the 1600s and into the 1700s, the debate over the nature of light was in full swing. Newton's theory of light particles faced challenges from leading scientists such as Christiaan Huygens. Huygens' writings on the wave theory of light described what we now call Huygens' principle and proposed that light travelled in waves through an omnipresent ether, like sound travelling through air. Mathematician and scientist Leonard Euler developed his own wave theory of light and used the particle theory's poor description of diffraction as a key point in an argument against Newton's theory.

During this time, many researchers focused on the question of interference. If light travels as a wave, then it should interfere like a wave; experiments looking for interference, however, could not detect it. We now know that the experiments failed because of the extremely small wavelengths of light. Interference patterns in water waves in ripple tanks are easy to observe, because the wavelengths are large and the frequencies of the sources are relatively small. These properties make the distance between adjacent nodal lines visible to the eye. Most experiments with light before the 1800s involved the placement of two sources of light close to each other, with screens positioned near the sources. The scientists closely observed the screens to try to observe interference patterns. They never succeeded using this method, partly because the separation between the nodal lines was too small to be observable. However, these issues did not account for all of the problems in attempting to repeat the ripple tank experiment with light waves.

Atoms, including those in the Sun and in light bulbs, emit most visible light. You might expect the light waves emitted by two atoms in the same source to be identical and have the same frequency so that they could exhibit interference. However, collisions among the atoms can reset the phase of the emitted light wave. Experiments show that these phase jumps in typical light waves occur about every 10^{-8} s. This means the light from different atoms of a given source is **incoherent** because the waves have no fixed phase relationship to each other.

If you direct light from a **monochromatic**, or single-wavelength, source through a narrow slit, however, the slit acts as a single point source, and the light travels from it as a coherent wave according to Huygens' principle. If you then direct the light from the single slit to a double slit (a closely spaced pair of slits), the double slit acts as a pair of sources of coherent, monochromatic light (**Figure 1**). Any change that occurs in the original source will occur in the two beams at the same time, which allows you to observe interference effects.

incoherent composed of waves that have no fixed phase relationship to each other and different frequencies

monochromatic composed of only one colour; light with one wavelength

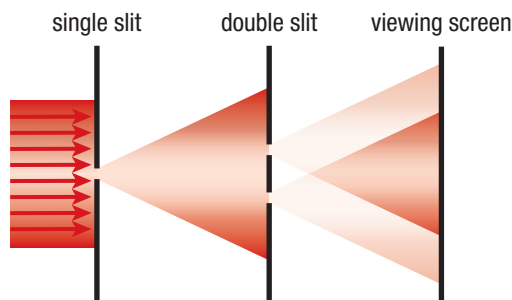


Figure 1 Monochromatic light passes through the single slit first, then through the double slit. According to Huygens' principle, both the single slit and the double slit act as a source of coherent light.



Figure 2 Thomas Young

Young's Double-Slit Experiment

At the very end of the 1700s, Thomas Young (**Figure 2**) performed a series of experiments to determine what happens when light passes through two closely spaced slits. We now refer to his basic setup as Young's double-slit experiment, and it demonstrated conclusively that light behaves as a wave. The experiment also provided a method to measure wavelength. **Figure 3(a)** shows the experimental setup, and **Figure 3(b)** shows an image produced with such a setup using white light.

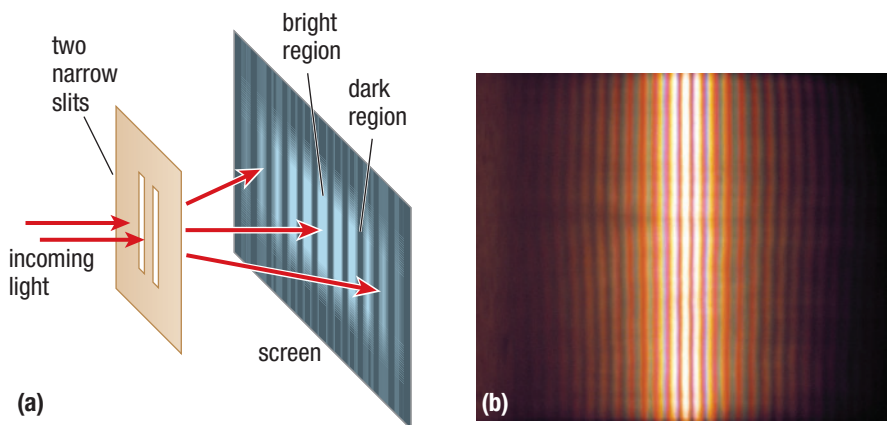


Figure 3 (a) Young used a similar setup in his light experiments in 1800. (b) When the white light passed through two small slits, an interference pattern of alternating bright and dark fringes was produced.

When monochromatic light, such as laser light, passes through the slits of an experiment setup similar to the one in **Figure 3(a)**, the laser light hits the screen on the right and produces an interference pattern. This arrangement satisfies the general conditions required to create wave interference:

- The interfering waves travel through different regions of space (in this case they travel through two different slits).
- The waves come together at a common point where they interfere (in this case the screen).
- The waves are coherent (in this case they come from the same monochromatic source).

When the two slits in the double-slit setup are both very narrow, each slit acts as a simple point source of new light waves, and the outgoing waves from each slit are like the simple spherical waves in **Figure 4**.

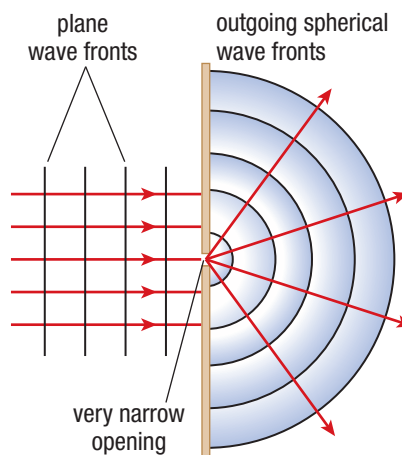


Figure 4 We can see the diffraction effects of light passing through two narrow slits by considering just one of the narrow slits. The same thing happens in the second narrow slit.

Investigation 9.5.1

Young's Double-Slit Experiment (page 490)

You have learned about Young's famous double-slit experiment. This investigation will give you an opportunity to recreate that experiment for yourself using a monochromatic light source and a series of different double-slit plates.

Interference will determine the intensity of light at any point on the screen. If one of the slits is covered, the screen shows a bright, wide centre line with closely spaced, dim, alternating dark and light bands, or **interference fringes**, on either side. You can read more about this single-slit pattern in Chapter 10. However, if both slits are open, then the screen shows a pattern of nearly uniform bright and dark fringes (**Figure 5**). The ideal double-slit pattern would show no dimming, but a real-world pattern does appear dimmer as you move away from the centre. This dimming occurs because the width of the slits causes each to act like a single slit, and the non-uniform single-slit pattern combines with the ideal double-slit pattern.

The bright and dark fringes are alternate regions of constructive and destructive interference, respectively. To analyze the interference, you need to determine the path length difference between each slit and the screen. **Figure 6** illustrates the double-slit interference conditions.

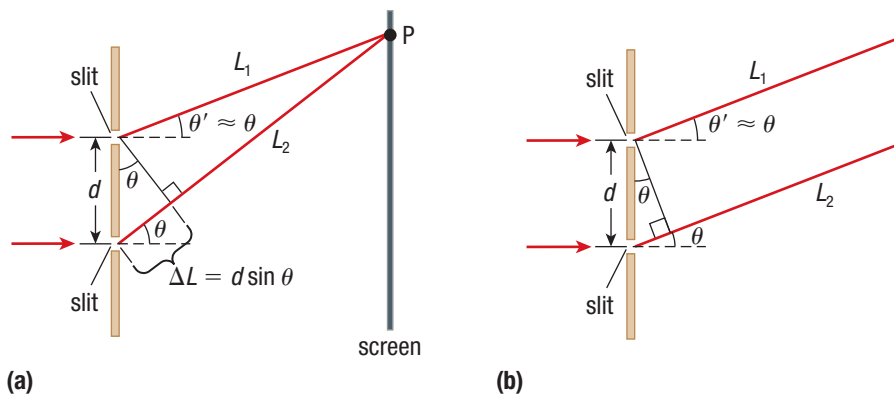


Figure 6 (a) Values of θ give the location of the bright fringes on the screen. (b) When the point P is very far away compared to the separation of the two sources, the lines L_1 and L_2 are nearly parallel.

To simplify the analysis in Figure 6, we will assume that the screen is a long way from the slits, so L is very large compared to d . The path lengths for waves from each of the slits to the point P on the screen are L_1 and L_2 in Figure 6. The distance L_2 is greater than the distance L_1 , and, since L is large, the angles that specify the directions from the slits to point P are approximately equal, so both are shown as θ in Figure 6. Finally, we assume that the wavelength λ is much smaller than d , the spacing between the slits.

Since the slits are separated by a distance d , the path length difference between L_2 and L_1 is given by

$$\Delta L = d \sin \theta$$

For the two waves to be in phase when they reach the screen, and thus for constructive interference to occur, this path length difference needs to be a whole number of wavelengths. The condition for constructive interference and a bright interference fringe is therefore

$$d \sin \theta = m \lambda$$

$$m = 0, 1, 2, 3, \dots$$

constructive interference

The light fringes, or **maxima**, are called zero-order maximum, first-order maximum, and so forth, for $m = 0, 1, 2, 3, \dots$. In this notation, $m = 0$ denotes the maximum in the centre of the screen. Successive values of m correspond to successive maxima moving away in either direction from the centre of the screen.

interference fringe one of a series of alternating light and dark regions that result from the interference of waves



Figure 5 A display of Young's double-slit experiment using red light

maxima points of brightness, or maximum intensity, in an interference pattern

For the two waves to be out of phase when they reach the screen, and thus for destructive interference to occur, the path length difference needs to be $\left(n - \frac{1}{2}\right)\lambda$. Thus, the condition for destructive interference and a dark fringe in the interference pattern is

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

$$n = 1, 2, 3, \dots$$

destructive interference

minima points of darkness, or minimum intensity, in an interference pattern

These dark lines, or **minima**, are called first-order minimum, second-order minimum, and so forth, for $n = 1, 2, 3, \dots$

Figure 7 shows a much-enlarged intensity pattern from a double-slit experiment. Notice that as the value of m changes, the angle θ also changes. At certain values of θ , the conditions for constructive interference are satisfied and a maximum in the intensity is produced, corresponding to a bright fringe. The fringe at the centre of the screen is the zero-order maximum and has the value 0 for m in the equation for constructive interference. The next bright fringe moving toward the top of the screen has the value $m = 1$, and so on.

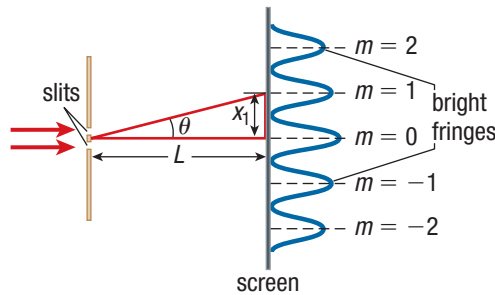


Figure 7 In this double-slit interference pattern, values of θ give the location of fringes on the screen.

How does the interference pattern change when the distance between the slits changes, or when the distance to the screen changes? First, calculate the separation between the central bright fringe ($m = 0$) and the next bright fringe ($m = 1$). The equation for constructive interference tells us that

$$\sin \theta = \frac{\lambda}{d}$$

To determine the separation between the bright fringes on the screen, you can use the right-angled triangle outlined in red in Figure 7. It has sides of lengths L and x_1 , where x_1 is the distance between the two fringes corresponding to $m = 0$ and $m = 1$. These lengths are related by the trigonometric relation

$$x_1 = L \tan \theta$$

The wavelength is much smaller than the spacing between the slits, so $\frac{\lambda}{d}$ is very small. Therefore, θ is also very small, and the approximation $\sin \theta \approx \tan \theta$ holds:

$$x_1 = L \sin \theta$$

$$x_1 = \frac{L\lambda}{d}$$

For the m th-order bright fringe, this relation becomes

$$x_m = \frac{mL\lambda}{d}$$

and the separation between any two adjacent fringes is

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

LEARNING TIP

Small-Angle Approximation

When L is much larger than y and the angle θ is small, $\sin \theta \approx \tan \theta$, so the tangent function is a good approximation to the sine function. You can verify this yourself by checking values on your calculator.

Suppose the slit separation is 0.1 mm, the wavelength of light from a red laser is 630 nm, and the screen is 0.5 m from the slits. Substitute the corresponding values into this equation to determine the separation of the fringes for the red laser light:

$$\begin{aligned}\Delta x &= \frac{L\lambda}{d} \\ &= \frac{(0.5 \text{ m})(6.3 \times 10^{-7} \text{ m})}{0.1 \times 10^{-3} \text{ m}} \\ &= 3.15 \times 10^{-3} \text{ m} \\ \Delta x &= 3.2 \text{ mm}\end{aligned}$$

This separation is large enough to be seen by the unaided eye.

This analysis shows that, provided the slits are close enough together, the bright and dark fringes in the interference pattern are observable. A slit separation of 0.1 mm or smaller works well. Experiments have shown that when the spacing is larger than a few millimetres, the fringes are close together and difficult to see.

Using the equations for destructive interference, you can calculate the distance of each dark fringe from the centre of the screen. The result is

$$x_n = \left(n - \frac{1}{2}\right) \frac{L\lambda}{d} \quad n = 1, 2, 3, \dots$$

For example, the distances of the first, second, and third minima from the centre of the screen are

$$\begin{aligned}x_1 &= \left(1 - \frac{1}{2}\right) \frac{L\lambda}{d} = \frac{L\lambda}{2d} \\ x_2 &= \left(2 - \frac{1}{2}\right) \frac{L\lambda}{d} = \frac{3L\lambda}{2d} \\ x_3 &= \left(3 - \frac{1}{2}\right) \frac{L\lambda}{d} = \frac{5L\lambda}{2d}\end{aligned}$$

Although L actually has different values for each nodal line, in this case L is so large compared to d and the values of L for the various nodal lines are so similar, that we can treat L as a constant, being essentially equal to the perpendicular distance from the slits to the screen.

Modern interference experiments often inject a cloud of smoke between the slits and the viewing screen. Some of the light reflects off the particles in the cloud, so the viewer can easily see the path of the light. Will interference patterns appear in the cloudy region between the slits and the screen? The equations for constructive and destructive interference depend on the distance, L , from the slits, which can be any value considerably greater than d . The interference patterns will still occur in both places. In the cloud region, you will see bright lines directed toward the bright areas of the screen and dark lines directed toward the dark areas of the screen.

The following Tutorial will demonstrate how to calculate physical quantities in double-slit interference patterns.

UNIT TASK BOOKMARK

You can apply what you have learned about interference and the double-slit experiment to the Unit Task on page 556.

Tutorial 1 Calculating Physical Quantities in Double-Slit Interference Patterns

The following Sample Problems show how to measure the wavelength of light and slit separation in a double-slit experiment.

Sample Problem 1: Determining the Wavelength of a Light Source

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

Given: $d = 0.41 \text{ mm} = 4.1 \times 10^{-4} \text{ m}$; $L = 1.5 \text{ m}$;
 $\Delta x = 1.5 \text{ mm} = 1.5 \times 10^{-3} \text{ m}$

Required: λ

Analysis: In a double-slit experiment, the bright fringes occur when light waves from the two slits interfere constructively. This happens when the path difference, ΔL , is equal to a whole number of wavelengths:

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

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

Solution:

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

$$= \frac{(1.5 \times 10^{-3} \text{ m})(4.1 \times 10^{-4} \text{ m})}{1.5 \text{ m}}$$

$$\lambda = 4.1 \times 10^{-7} \text{ m}$$

Statement: The wavelength of the light is $4.1 \times 10^{-7} \text{ m}$.

Sample Problem 2: Determining Slit Separation

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.

Given: $n = 3$; $\theta_3 = 20.0^\circ$; $\lambda = 660 \text{ nm} = 6.6 \times 10^{-7} \text{ m}$

Required: d

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

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

Solution:

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

$$= \frac{\left(3 - \frac{1}{2}\right)(6.6 \times 10^{-7} \text{ m})}{\sin 20.0^\circ}$$

$$d = 4.8 \times 10^{-6} \text{ m}$$

Statement: The slit separation is $4.8 \times 10^{-6} \text{ m}$.

Practice

1. Calculate the wavelength of the monochromatic light that produces a fifth-order dark fringe at an angle of 3.8° with a slit separation of 0.042 mm. **T/I** [ans: $6.2 \times 10^{-7} \text{ m}$]
2. Two slits are separated by a distance of 0.050 mm. A monochromatic beam of light with a wavelength of 656 nm falls on the slits and produces an interference pattern on a screen that is 2.6 m from the slits. Calculate the fringe separation at the centre of the pattern. **T/I** [ans: 3.4 cm]
3. The third-order dark fringe of light with a wavelength of 652 nm is observed when light passes through two double slits onto a screen. The slit distance is $6.3 \times 10^{-6} \text{ m}$. At what angle is the fringe observed? **T/I** [ans: 15°]

More Developments in the Theory of Light

Young's evidence for the wave nature of light was not accepted by the scientific community until 1818, when Augustin Fresnel proposed his own wave theory, complete with the mathematics. A mathematician named Simon Poisson showed how Fresnel's equations predicted a unique diffraction pattern when light is projected past a small solid object, as shown in **Figure 8**.

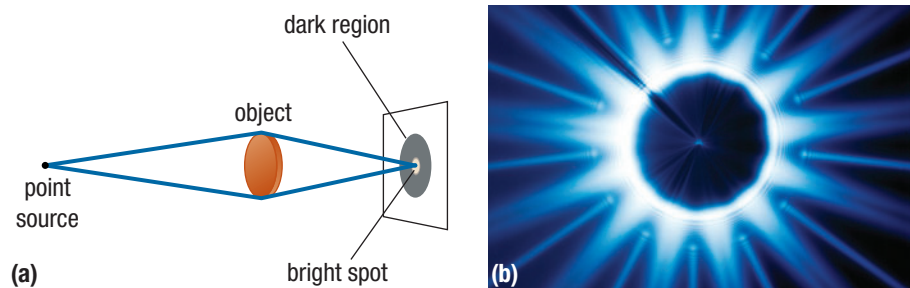


Figure 8 (a) The prediction of Fresnel and Poisson, confirmed by Arago, says that diffraction will cause a small bright spot to appear at the centre of the shadow of a small solid object. (b) A small disc refracts light and shows Poisson's bright spot.

Poisson's argument was that, if light behaved as a wave, then the light diffracting around the edges of the disc should interfere constructively to produce a bright spot at the centre of the diffraction pattern. This was impossible according to the particle theory of light. In 1818, Poisson's prediction was tested experimentally by Dominique Arago, and, to many people's surprise, he successfully observed the bright spot.

Arago's experiment demonstrated what is now called "Poisson's bright spot." The wave theory had been generally accepted by 1850, although it could not explain the movement of light through a vacuum such as space. Therefore, as mentioned in Section 9.4, scientists developed a theory that a fluid called ether filled all regions of space. Despite many experiments devised to try to detect this ether, it was never found.

Mini Investigation


Wavelengths of Light

Skills: Performing, Observing, Analyzing, Communicating

SKILLS
HANDBOOK  A2.1

In this investigation, you will answer the question, "What are some of the wavelengths that constitute white light?"

Equipment and Materials: clear showcase lamp; rotor stand and clamp; white screen; ruler; paper sliders; red and green transparent filters; double-slit plate; metre stick; elastic bands

1. Set up the apparatus as shown in **Figure 9**. View the lamp through the double slit and describe the pattern seen on either side of it. 

 If a lamp is used, unplug it by pulling on the plug, not the cord.

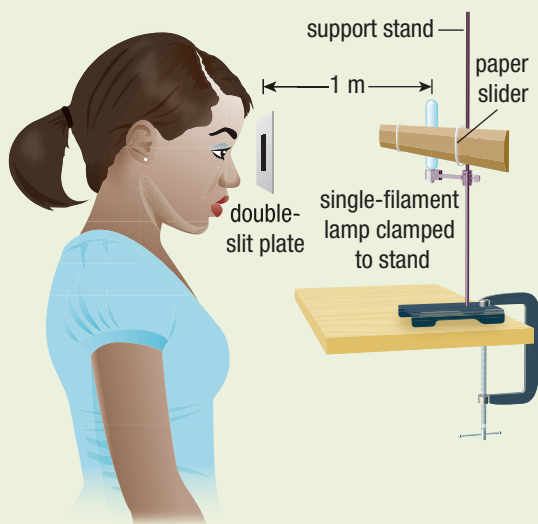


Figure 9 Setup for the wavelength experiment

2. Cover the upper half of the bulb with the green filter and the lower half with the red filter, securing each filter with elastic bands. Compare the interference patterns for green and red light.
3. Cover the lamp completely with the red filter. Use the ruler mounted in front of the light to count the number of nodal lines you can see in a fixed distance. Use the paper sliders to mark the distance on the ruler.
4. Predict the relative wavelengths of red and green light.
5. Leaving the paper sliders in place, repeat Step 3 with the green filter.
6. Record the number of bright fringes between the markers and the distance between the paper sliders. Calculate the average separation, Δx , of the nodal lines.
7. Use the relationship $\frac{\Delta x}{L} = \frac{\lambda}{d}$ to determine the wavelength of that colour of light (d should be recorded on your slit plate or should be available from your teacher).
8. Compare your results with those of other students.
 - A. Describe the interference patterns you saw for each filter. T/I C A
 - B. How many nodal lines did you see at a fixed distance for each filter? T/I
 - C. Calculate the wavelength of the colour of light for each filter. T/I

9.5 Review

Summary

- Earlier experiments that attempted to show the interference of light using two sources of light some distance apart were unsuccessful because the sources of light were out of phase and the wavelength of light is so small.
- Thomas Young's successful experiment used diffraction through a double slit to create two sources of light from a single coherent source of light so that the sources were close together and in phase.
- Young's experiment produced a series of light and dark fringes on a screen placed in the path of the light, with a pattern that resembled the results of interference of water waves in a ripple tank.
- For a setup with slit separation d and light of wavelength λ , the locations of bright fringes are given by $d \sin \theta = m\lambda$, for $m = 0, 1, 2, 3, \dots$, and the locations of dark fringes are given by $d \sin \theta = \left(n - \frac{1}{2}\right)\lambda$, for $n = 1, 2, 3, \dots$
- For a viewing screen at a distance L , the m th-order bright fringe is at location $x_m = \frac{mL\lambda}{d}$, and the n th-order bright fringe is at location $x_n = \left(n - \frac{1}{2}\right)\frac{L\lambda}{d}$.
- Young's diffraction experiment was evidence for the wave nature of light. The wave theory could explain all properties of light except its propagation through a vacuum.

Questions

1. How is the interference pattern produced by monochromatic red light, $\lambda = 650$ nm, different from the pattern produced by monochromatic blue light, $\lambda = 470$ nm, when all other factors are kept constant? **K/U**
2. When a monochromatic light source shines through a double slit with a slit separation of 0.20 mm onto a screen 3.5 m away, the first dark band in the pattern appears 4.6 mm from the centre of the bright band. Calculate the wavelength of the light. **T/I**
3. Suppose a double-slit experiment is carried out first in air, then completely underwater, with all factors being the same in each medium. How do the interference patterns differ? **K/U T/I**
4. Two slits are separated by 0.30 mm and produce an interference pattern. The fifth minimum is 1.28×10^{-1} m from the central maximum. The wavelength of the light used is 4.5×10^{-7} m. Determine the distance at which the screen is placed. **T/I**
5. In a double-slit experiment, the distance to the screen is 2.0 m, the slits are 0.15 mm apart, and the dark fringes are 0.56 cm apart. **T/I**
 - (a) Determine the wavelength of the source.
 - (b) Determine the spacing of the dark fringes with a source of wavelength 600 nm.
6. The second-order dark angle in a double-slit experiment is 5.4° . Calculate the ratio of the separation of the slits to the wavelength of the light. **T/I**
7. In a double-slit experiment, the slits are 0.80 mm apart and an interference pattern forms on a screen, which is 49 cm from the slits. The distance between adjacent dark fringes is 0.33 mm. **T/I**
 - (a) Determine which wavelength of monochromatic light is used in this experiment.
 - (b) Determine the distance between the fringes if the same light were used in an experiment with slits that were 0.60 mm apart.
8. Light with a wavelength of 5.1×10^{-7} m passes through a double slit and onto a screen that is 2.5 m from the slits. **T/I**
 - (a) Determine the slit spacing if two adjacent bright fringes are 12 mm apart.
 - (b) If the slit spacing is now reduced by a factor of three, determine the new distance between the bright fringes.
9. Summarize the development in the theory of light. Can light be considered a wave only and not a particle? Why or why not? **K/U**