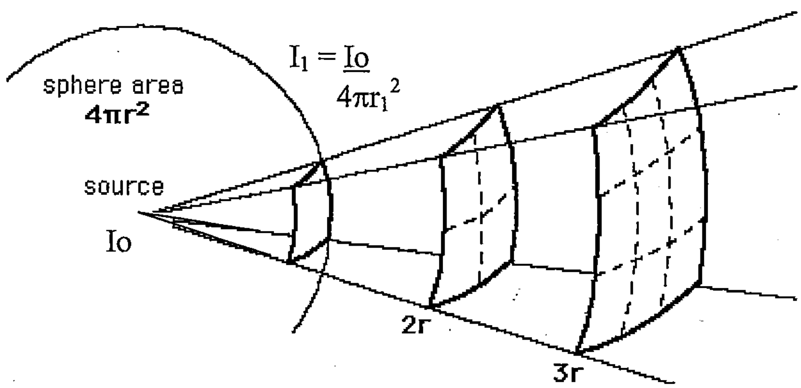
The Wave Nature of Light

Electro-magnetic waves (including light) has been known to exhibit wave properties for centuries, in order to fully show how these properties relate to light we must look through some important wave properties that apply to all waves, not just EM waves.

Waves spread out in a spherical form from their source, this may seem circular in the case of water waves on a surface but this is because very little of the wave's energy transmits from the water into air.

As the wave travels farther from its source it travels a radial distance $r = v\,t$ where v is the wave's speed and t is the elapsed time from the source emitting a particular pulse.

The intensity of light at any radius of a light wave (or volume of sound) is found as $I = Io / 4\pi r^2$. Where Io is the intensity (brightness) of the source.



At t_1 the wave front is at r, at t_2 it is at 2r, at t_3 at 3r. Then the intensity I at t2 must be:

$I_1 = \frac{Io}{4\,\pi\,r_1^2}$ and $I_2 = \frac{Io}{4\,\pi\,r_2^2}$ at t_2 $r_2 = 2r_1$ so: $I_2 = \frac{Io}{4\,\pi\,(2r_1)^2}$ or $I_2 = \frac{Io}{4\pi\,4r_1^2}$

But substitution for $I_1 = Io / 4\,\pi\,r_1^2$ gives us:

$I_2 = I_1 / 4$

The relation above illustrates that the intensity of a light wave (or any wave) obeys the inverse square law, as the wave Energy is spread over a surface area increasing as a function of r^2.

Also recall that the speed of the wave is the product of its wavelength λ and frequency f so that $v = \lambda\,f$.

Luminous objects glow, they are sources of light. Things which are illuminated reflect light from light sources.

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Luminous Intensity Lab

Purpose: to determine the relationship between luminous Intensity and radial distance from a source

Procedure:

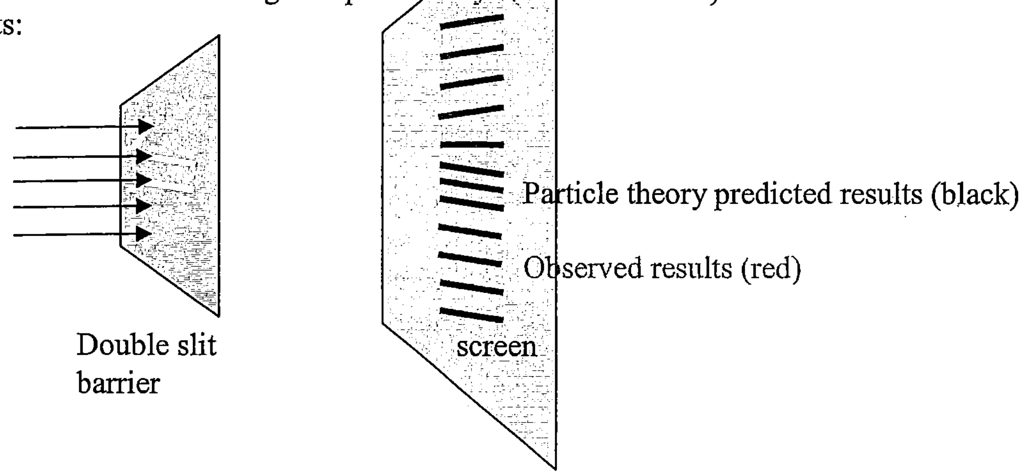
1) Obtain a labquest and the light sensor; ensure the light sensor's toggle switch is set to 0 – 6000 lux.
2) Cover the light sensor with your hand and zero it by clicking on the red box and touching zero.
3) Press Sensor then Data Collection. Set the mode to Events with Entry. Set the name to Distance and the units to cm. Press Ok, then the play button in the bottom left.
4) Obtain a reading of Φ_L by holding the light sensor 4.0 cm from the source and press keep to take a reading. Type in the distance and press Ok. Repeat every 0.5 cm until 8.0 cm.
5) Continue to take Φ_L readings every 2.0 cm until 20.0 cm is reached, and then press the stop button.
6) Connect your labquest unit to a computer and open Logger Lite. Once your data is loaded in Logger Lite, press file, export as, CSV. Save the file.
7) Open the file you just saved in excel. Insert 2 columns between Distance and Illuminance. Title them 1/d and 1/d^2, respectively.
8) In cell B2, type =1/A2. Select the cell and drag the black square in the corner down to the end of your data. Repeat in cell C2, instead typing =1/A2^2.
9) Using Excel's graphing capabilities have it run a scatter plot of Φ_L vs. d. Right click on a point and select add trendline, check show equation and select power to get an equation of your data. Title the graph and appropriately label axes.
10) Now do the same as Φ_L vs. d^2.
11) Now do the same as Φ_L vs. d^{-2}, but select linear instead of power.
12) Print your graphs and data.

Discussion:

1) What is the value of Io and how can it be found from your last graph?
2) What is the physical significance of the y-intercept of your last graph?

Conclusion: What proof is shown the relation between Φ_L and d is inverse square?

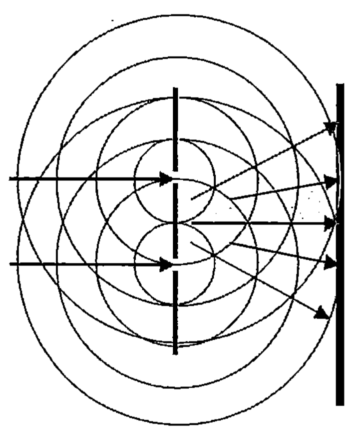
Diffraction: the bending of waves around an object
Light was believed to be a particle as phenomena like diffraction were not observed in light (in reality this is because normal openings and obstacles are much larger than the wavelength of visible light so little bending or diffraction occurs). Grimaldi (early 1600's) using careful observations and geometry found the bright spot on the far wall of a darkened room was larger than geometry allowed. This concept was not verified until 1801 by Young in the double slit experiment. Here incident light of parallel rays (a far off source) is shone at 90° to a surface with two slits:



Young explained the results as diffraction causing constructive interference between wavelets created using Huygen's principle as the incident light emerges as a wave from each slit. See below:

When the wavelets from one slit travel exactly 1 wavelength farther than those from the other slit, the crests constructively interfere, causing a bright spot. This occurs at any extradistance = whole multiple of λ. Thin red rays illustrate this.

Destructive interference, no light occurs were a crest meets a trough on the screen, shown with the thin black rays. This is because one ray has travelled a whole multiple of ½ λ farther and crest meets trough.

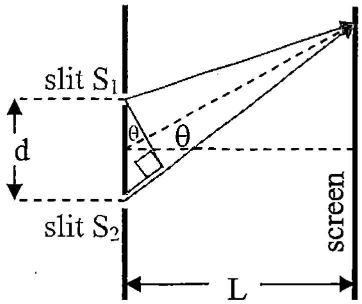


1st order maxima, slightly dimmer than central maxima, green crests travel 1 λ farther than blue

Central maxima, highest intensity as waves travel shortest distance

1st order maxima, blue wave crests travel exactly 1 λ farther than green crests

Using geometry and slit separation we can find a relation between the angle from centre of the slits and the maxima of various order.



1st order maxima occurs when blue ray has traveled an extra distance of one wavelength greater than the green ray

Angle θ is drawn from the central maxima to the mid-point between slits S1 & S2 to the 1st (or higher) order maxima

In the red triangle the red angle at S1 corresponds to θ and is therefore θ

The extra distance travelled by the blue ray then becomes the opposite to θ which is $d \sin \theta$ for small angles. So $d \sin q = l$ for the first order maxima. The next maxima (2nd order) occurs when $d \sin \theta = 2 \lambda$ or generally:

$$d \sin \theta = m \lambda$$ where m is the order of the maxima

If the distance to the screen L is known then the physical distance from central maxima to the 1st (or higher order) maxima can be found using geometry. Similarly one could measure the distance to the 1st order from central maximum and L to find q then d or λ if the other is known.

Minima occur when the light travels an extra multiple of ½ λ.
So minima occur at $d \sin \theta = (m + ½) \lambda$.

Young's careful measurements and theory set light (and all EM waves) firmly as a wave. Since the function includes wavelength it is useful to use light of only one wavelength or colour as different λ will diffract on different angles. Therefore most experiments use **monochromatic** light.

Problems:

1) A light bulb produces 1600 lumens of light energy at its point source. What is its luminosity 1.0 m away? What is its luminosity 3.0 m away?
2) What is the wavelength of monochromatic light which is coherent and falls on double slits separated by 19 μm if the 1st order maximum is 13.2 mm from central max and the screen is 60 cm from the slits?
3) If light from a sodium vapour lamp (monochromatic at 596 nm) is used for the same physical setup as in 2 above what will be measured between central max and the 1st order minima and the 1st order maxima?
4) A laser of $\lambda = 632.8$ nm is used in a double slit experiment with a screen 1.00 m away and the 2nd order maximum is 13.2 cm from the central max, what is the slit separation?

Ans. 1a) 127.3 lumens 1b) 1.41 lumens 2) 418 nm 3) to 1st minima = 9.41 mm, to 1st maxima = 18.7 mm 4) 9.66 μm

E. Huygens principle 24-1,24-2

1) Illustrate and decribe Huygens principle. What wave behavior does it explain?

F. Interference -- Youngs double-slit experiment 24-3

1) Read carefully how double slits produce an interference pattern. List and describe the equations for destructive and constructive interference. (** see if you can see how they were derived**)

2) Draw a typical intensity vs angle graph. Fig 24-10

3) Study examples 24-1, 24-3. Note for small angles **sin@ = tan@ = x/l.**

14] The second-order fringe when 700 nm light falls on two slits is observed at a 15 deg angle to the initial beam direction. How far apart are the slits? (5.41×10^{-6} m)

15] Monochromatic light falling on two slits 0.026 nm apart produces the fourth-order fringe at a 6.4 deg angle. What is the wavelength of the light used? (7.25×10^{-13} m)

16] A parallel beam of 600 nm light falls on two small slits 0.05 mm apart. How far apart are the fringes on a screen 5.0 m away? (6.0 cm)

17] Light of wavelength 680 nm falls on two slits and produces an interference pattern in which the fourth-order fringe is 28 mm from the central fringe on a screen 1.0 m away. What is the separation of the two slits? (9.71×10^{-5} m)

G. The visible spectrum 24-4

H. Diffration by a single slit or disc 24-5

1) Draw a typical intensity vs angle graph for a single slit. Fig 24-20

2) List and describe a formula used to calculate the interference pattern produced by a single slit. **Try** to determine how it was derived.

18] Monochromatic light falls on a slit 3.5×10^{-3} mm wide. If the angle between the first bright fringes on either side of the central maximum is 38.0 degs, what is the λ? (760 nm)

Diffraction grating 24-6

1) What is a diffraction grating?

2) List and describe the formula that describes the interference pattern produced by a diffration grating.

3) How is the interference pattern produced by a diffraction grating different then that produced by double slits.

4) Draw a typical intensity vs angle graph for a difraction grating of a] 2 slits and b] 6 slits Fig. 24-24

19] The first-order line of 550 nm light falling on a diffration grating is observed at a 12 deg angle. How far apart are the slits?
(2.65×10^{-6} m)

20] At what angle will 710 nm light produce a third-order maximum when falling on a grating whose slits are 0.0017 cm apart? (7.2 deg)

21] How many lines per centimeter does a grating have if the third-order occurs at a 22.0 deg angle for 650 nm light? (1921 lines/cm)
find d in cm's and divide d into 1 cm

J. The Spectroscope 24-7

K. Interference by thin films 24-8

1) What are some examples of interference by thin films?

2) **Explain how thin film interference occurs. Use Fig 24-25 to help.

3) What are Newton's rings?

4) Why is the point of contact of the two glass surfaces dark????

L. Michelson interferometer 24-9 -used to do famous Michelson-Morley experiment (Relativity)

M. Polarization 24-10

1) What is polarized light?

2) Why do polarized sunglasses help you see under the water?

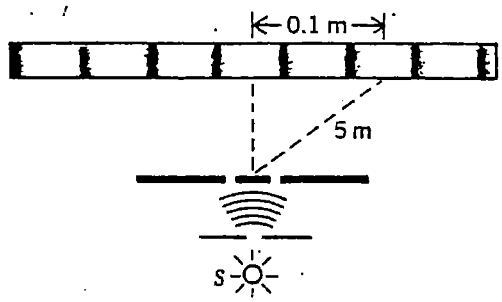
3. The fact that a light wave can pass through a 10 cm opening without being diffracted to any great extent indicates that the wavelength of the light is
a. exactly 10 cm
b. slightly more than 10 cm
c. much more than 10 cm
d. much less than 10 cm
✓3......

4. On a water surface, two sources generate waves that overlap each other. The regions in which there is no wave motion are
a. nodal lines
b. maximums
c. troughs
d. crests
✓4......

5. A single-slit diffraction pattern is produced by a beam of light. The distance between any two adjacent minimums may be increased by
a. changing to light of a lower frequency
b. changing to light of a higher frequency
c. increasing the width of the slit
d. increasing the intensity of the light
✓5......

Study the information below; then complete statements 6-8.

Light of given wavelength passes through a narrow slit and then passes through two slits 5×10^{-5} m apart. The pattern that appears on the screen is shown in the diagram.



6. The wavelength of the light is
a. 1×10^{-6} m
b. 5×10^{-7} m
c. 5×10^{3} m
d. 1.25×10^{-3} m
✓6......

7. If light of a longer wavelength is used, the maximums on the pattern will
a. move closer to the center
b. move away from the center
c. retain their present positions
d. increase in intensity
✓7......

8. If the distance between the slits is decreased, the minimums on the pattern will
a. move closer to the center
b. move away from the center
c. retain their present positions
d. increase in intensity
✓8......

11. Two rays will interfere constructively with maximum amplitude if the path difference between them is
a. $n\lambda$
b. $n\lambda/2$
c. $n\lambda/4$
d. $n\lambda/8$
✓11......

same as double slit →

12. Two point sources, 8 cm apart and operating in phase in a ripple tank, produce an interference pattern. A point on the first nodal line is 12 cm from the center line and 80 cm from a point midway between the two sources. The wavelength of the waves in the pattern is
a. 1.2 cm
b. 2.4 cm
c. 3.6 cm
d. 4.8 cm
✓12......

13. Interference between the component rays of a single broad wavefront results in
a. refraction
b. reflection
c. diffusion
d. diffraction
omit 13...

$1 Å = 10^{-10}$ m

14. A beam of light of a single wavelength passes perpendicularly through a slit whose width is 1.0×10^{-4} m. A pattern appears on a screen 1.0 m from the slit. If the distance from the first maximum to the center line is 5.0×10^{-3} m, the wavelength of the light is
a. 1000 Å
b. 4000 Å
c. 5000 Å
d. 3333 Å
✓14......

15. The resultant amplitude of waves passing through a single slit is zero when the path difference between the waves is

a. $\lambda/8$
b. $\lambda/4$
c. $\lambda/2$
d. λ

✓ 15......

16. Light bends around sharp corners as a result of

a. refraction
b. reflection
c. diffraction
d. dispersion

✓ 16......

17. In an experiment with a double slit, the first maximum appears at an angle θ_1 from the center line. If the space between the slits is halved, the first maximum now appears at an angle of θ_2 from the center line. The relation between θ_1 and θ_2 is

a. $\theta_1 = \theta_2$
b. $\theta_2 = 2\theta_1$
c. $\sin \theta_1 = 2 \sin \theta_2$
d. $\sin \theta_2 = 2 \sin \theta_1$

✓ 17......

Name .... Date .... Class ....

Study the paragraph below; then complete statements 18-20.

A beam of light of a single wavelength ($\lambda = 4.5 \times 10^{-7}$ m) is directed at two parallel slits, S_1 and S_2, which are 3.0×10^{-4} m apart. An interference pattern appears on a screen 9.0×10^{-1} m from the slits.

18. The difference in the lengths of the paths from S_1 and S_2 to the second maximum is

a. $\lambda/2$
b. λ
c. $3\lambda/2$
d. 2λ

✓ 18......

19. The distance from the midpoint of the second maximum to the center line is

a. 3.0×10^{-10} m
b. 2.7×10^{-3} m
c. 6.0×10^{2} m
d. 6.1×10^{-12} m

✓ 19......

20. The frequency of the light is

a. 1.5×10^{-15} Hz
b. 1.4×10^{1} Hz
c. 6.7×10^{14} Hz
d. 3.0×10^{8} Hz

✓ 20......

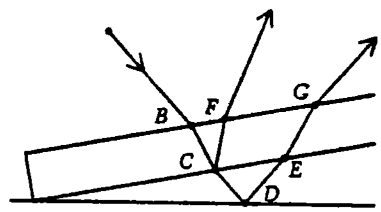
Name . . . . Date . . . . Class . . . .

CHAPTER 23: Applications of Wave Optics

Select the term that best completes each of the following statements. Place the letter of the term you choose in the space provided for the answer.

1. Monochromatic light consists of
   a. only one wavelength
   b. a band of 10 wavelengths
   c. a band of 100 wavelengths
   d. a band of 1,000,000 wavelengths
   1......

2. As shown in the diagram, ray A is reflected at points
   a. C and D
   b. C and E
   c. D and G
   d. E and G
   2......

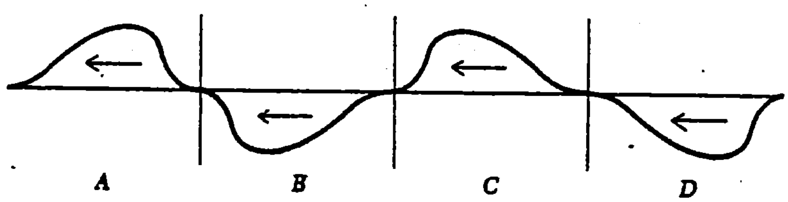


3. A series of bright and dark bands are seen when looking at an air wedge. A bright band A is followed by a dark band and then another bright band B. The total path difference between bright band A and B is
   a. $\lambda/4$
   b. $\lambda/2$
   c. λ
   d. 2λ
   3......

4. Light of wavelength 5000 Å illuminates an air wedge 100 cm long with the top layer of glass 0.05 cm above the lower layer of glass at the open end. The distance between successive dark bands is
   a. 1.25×10^{-12} cm
   b. 5.0×10^{-2} cm
   c. 5.0×10^{2} cm
   d. 2.0×10^{5} cm
   4......

Study carefully the information below; then complete statements 5-7.

The diagram at the right shows a pulse sent along a rope. The diagram below shows four sections, each a possible reflected pulse, labeled A, B, C, and D.



5. If the end of the rope is attached to a rigid wall, the reflected pulse will look like that in section
   a. A
   b. B
   c. C
   d. D
   5......

6. If the end of the rope is unattached, the reflected pulse will look like that in section
   a. A
   b. B
   c. C
   d. D
   6......

7. If the speed of the original pulse is 2 m/sec, the speed of the reflected pulse will be
   a. 0.5 m/sec
   b. 1 m/sec
   c. 2 m/sec
   d. 4 m/sec
   7......

Select the term that best completes each of the following statements.

8. Light of wavelength λ is directed at a thin soap film. The light will experience complete destructive interference if the film thickness is
a. $\lambda/8$
b. $\lambda/4$
c. $\lambda/2$
d. $3\lambda/4$

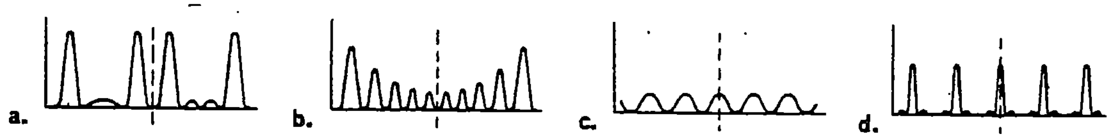
9. The Michelson interferometer provided experimental evidence that the speed of light is
a. greater than the speed of sound
b. independent of the observer's motion
c. impossible to measure
d. dependent upon the medium in which it travels 9.

10. An experimenter working with a Michelson interferometer sees 200 fringes moving past a reference point as the mirror on the device is moved 5.0×10^{-5} m. The wavelength of the light being observed is
a. 2500 Å
b. 4000 Å
c. 5000 Å
d. 8000 Å 0.....

11. The maximum of the interference pattern formed by a diffraction grating compared with those of a double slit are
a. fuzzier and dimmer
b. fuzzier and brighter
c. sharper and dimmer
d. sharper and brighter 11.....

12. The prism in a spectroscope separates light into its component colors by
a. refraction
b. reflection
c. diffraction
d. interference 12.....

13. The relation between the intensity of light I and the distance from the center line C of an interference pattern formed by a diffraction grating is best shown by graph

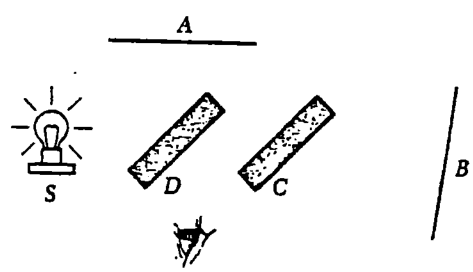


13.....

14. A spectral line must be light
a. of a single wavelength
b. from two sources
c. from a low-intensity source
d. from a star 14.....

15. The greater the ability of a spectroscope to separate two colors of almost the same wavelength, the greater its
a. grating space
b. slit width
c. eyepiece magnification
d. resolving power

16. In the diagram of the Michelson interferometer, the half-silvered mirror used to split the light from source S is at
a. *A*
b. *B*
c. *C*
d. *D*



16.

17. A diffraction grating has 2000 lines/cm. The space between the centers of the slits of the grating is
a. 2000 Å
b. 5000 Å
c. 10,000 Å
d. 50,000 Å 17.....

