Chapter 23 WAVES AND LIGHT

We saw in the last chapter that the behavior of waves on springs or ropes was analogous to the observed behavior of light in many circumstances. However, that model using springs was very limited. Since many of the phenomena we observe with light are two-dimensional in nature, we need a wave model for light that extends to two dimensions, and will use a very common phenomenon - water waves - as the basis for our model.

We will compare this water wave model to the actual behavior of light and discover that the model does an excellent job of predicting this behavior. We will discover that this model predicts an effect called diffraction which is not ordinarily seen by the naked eye. And having pretty well established that light does indeed behave like a wave, we will obtain an estimate of the "size" of light waves.

PERFORMANCE OBJECTIVES

After completing this chapter, you should be able to

1. Use the wave front and reflecting barrier to determine the angle of incidence and the angle of reflection; and given the boundary location between water of two depths, be able to determine the angle of incidence and the angle of refraction using the wave fronts.

2. Demonstrate in a ripple tank the following:
   a. straight and circular pulse reflections from various shaped surfaces,
   b. refraction of waves as they pass from water of one depth to water of a different depth,
   c. partial reflection and refraction
   d. dispersion of waves as they pass through openings,
   e. scattering of waves around obstacles.

3. Explain how the behavior of two-dimensional water waves serves as a good model for the following behavior of light:
   a. reflection,
   b. refraction,
   c. varying velocities of light in different mediums,
   d. partial reflection and refraction,
   e. dispersion of light as it passes through small openings,
   f. scattering of light as it passes an obstacle.

4. Experimentally determine the wave length and frequency of a water wave.

5. Calculate the velocity of a water wave using the wave equation.

6. Verbally summarize the evidence obtained that light must have a very small wave length.

1. Much of your time will be spent in the laboratory using the ripple tank to produce observable characteristics of wave phenomena in two-dimensions. Your reporting of experimentation using the ripple tank (only) will take on the following format.

. . . .

. What you do or are going to do is considered the procedure. In concise, proper English, you are to state one thing that you are going to do beginning near the left side of the paper.

Now indent and record your observations. This may be written descriptions, data, analysis, a sketch, or . . . which will best communicate your observations.

A further indention will contain your conclusion. You should at all time be looking for the analogy between the behavior of water waves and the behavior of light.

. . . .

That which is shown above is an example of the way you **must** report your findings of all experimentation with the ripple tank. Thus for each and every new procedure you are to repeat the above reporting process. At the end of each day, you are to submit the report of that days work to your instructor for evaluation. The report will be evaluated and returned the next day. Thus it is necessary that you write up each activity as it is completed.

.....Any questions? Ask now.....

2. Read: Section 23-1 Water Waves page 465
   23-2 Straight and Circular Pulses page 466
   23-3 Reflection page 467

3. Examine Figure 23-1 and 23-2, page 465 along with transparency 40-E. (See enclosed sheet which shows the transparency in miniature. You may use this or the regular size transparency.) How would the focal length of the lens-effect of the crests and troughs change if:

   a. the distance between crests increased?

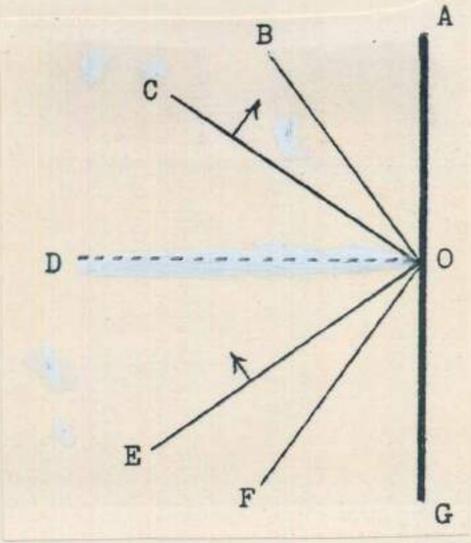
   b. the amplitude of the waves increased?

   c. the screen was lowered?

   d. the lamp was raised?

4. Examine Figures 23-6, 23-7 and 23-8 on pages 468 and 469. You might also use transparency 40-K. Satisfy yourself that the angle of incidence and the angle of reflection can be determined by using the wave front and the barrier rather than the direction of propagation and the normal relative to the reflection surface.

5. On the diagram at the right, lines CO and EO are crests of a wave that is partly reflected from the barrier. Arrows indicate direction of motion.



a. Which is the incident pulse?

b. Which is the reflected pulse?

c. Which (is/are) the angle(s) of incidence and which (is/are) the angle(s) of reflection?

6. Problems: page 467: #1 #2 #3 #4

7. Experiment: PULSES IN A RIPPLE TANK" (Directions provided.)

a. Remember to follow **special** write-up procedure.

b. The write-up is due each day for that days activities.

8. Problems: page 470: #5 #6 #7 #8
482: #21 #22 #23

9. Experiment: PERIODIC WAVES (Directions provided.)

10. Read: Section 23-4 Speed of Propagation & Periodic Waves page 470

a. Transparency 40-L may possess some valuable information.

b. Justify that v = f comes from v = d/t.

11. Problems: page 474: #9 #10 #11 #12 #13

12. As a wave approaches the beach, does it speed up or slow down?

13. Experiment: REFRACTION OF WAVES (Directions provided.)

14. Read: Section 23-5 Refraction page 474
23-6 Dispersion page 478

15. Problems: page 478: #15 #16 #17
page 483: #26 #27 #28 #29

16. From what you have done so far, is the wave length of blue light greater or less than the wave length of red light? A written summary is necessary.

17. Experiment: WAVES AND OBSTACLES (Directions provided.)

Due to excess vibrations, you might not be able to see all that it is hoped that you will see. Therefore, you may wish to view the following Film Loops and Transparencies after you have completed the experiment. You may wish to view them before experimenting and if time is limited, not do the experimenting.

a. Film Loop RT-14: Single Slit Diffraction of Waves
b. Film Loop RT-16: Diffraction & Scattering of Waves Around Obstacles
c. Transparency 40-Q: Diffraction
d. Transparency 40-R: Diffraction

18. Read: Section 32-7 Diffraction page 480

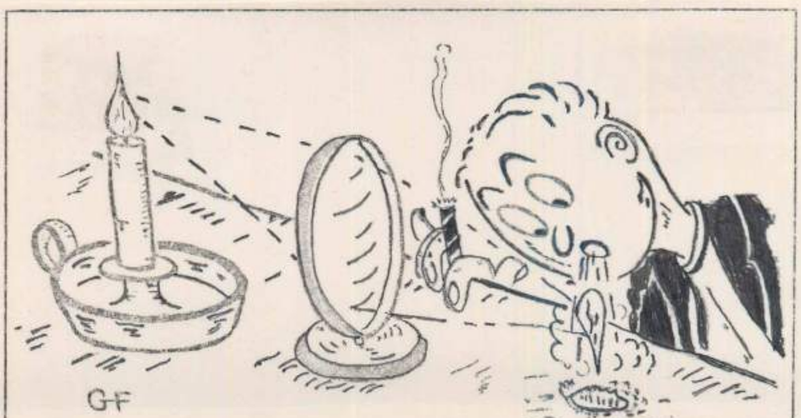
19. Problems: page 482: #18 #19
#30 #31 #32 #33 #34

20. Must light have a very small wavelength? Think about this. What have you done that indicates that it does or does not have a very small wavelength?

21. Now read: REVIEW OF THE ARGUMENT THAT LIGHT MUST HAVE A VERY SMALL WAVELENGTH that is enclosed in this packet. Any questions? Discuss them with your instructor.

22. Complete the enclosed one-page written exercise and have it evaluated.

23. Request end of chapter test, complete and have it evaluated.



ANSWERS CHAPTER 23

3\. (a) 'f' increases (b) 'f' decreases
(c)(d) no change in 'f' - changing the light could help the focus

5\. (a) CO (b) EO
(c) angle of incidence = 55°: DOF and AOC
angle of reflection = 55°: BOD AND EOG

6\. (1) About 20 cm long
(2) At right angles to its crest
(3) (4) S.A.B.

8\. (5) 25°
(6) (a) incident pulse: (2), reflected pulse: (1) (b) 70°
(7) (8) (21) (22) (23) S.A.B.

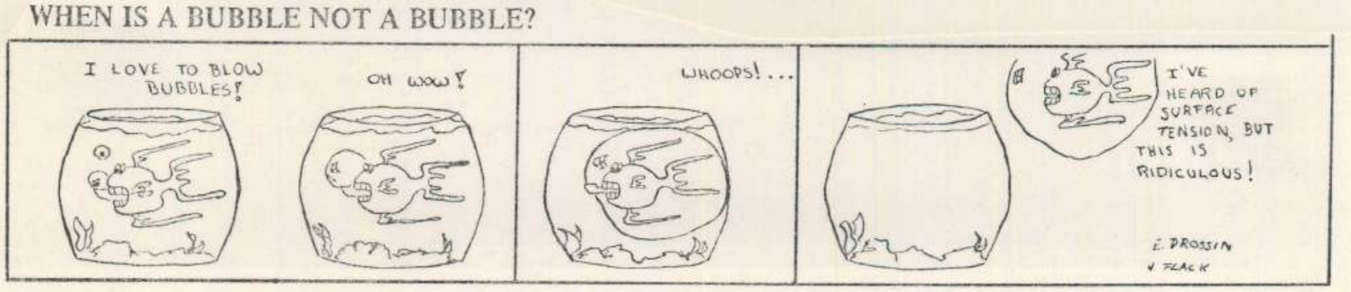
11\. (9) (a) 85 m (b) It decreases
(10) (a) 1/4 sec (b) 4 Hertz
(11) Decrease the frequency
(12) (a) 30 cm/sec (b) 15 cm
(13) S.A.B.

12\. Discuss with your instructor.

15\. (15) approximately 1.8
(16) ratio of wavelengths approximately 1.7
ratio of sines of the angles approximately 1.7
(17) (a) 1.23 (b) 20.3 cm/sec
(26) no, not unless one 'f' was a whole number multiple of the other
(27) (a) 440 m/min (b) 1.8×10^{10} cm/s (c) 5×10^{-5} cm in vacuum (d) 1.7
(28) S.A.B.
(29) (a) 38° 41° (b) by measuring the angles
(c) by measuring difference in angles of refraction

19\. (18) (19) (30) (31) (32) (33) S.A.B.
(34) 11 meters 0.022 meters

WHEN IS A BUBBLE NOT A BUBBLE?



CONTENTS SHEET • SCIENCE NO. 40

PHYSICS – WAVES

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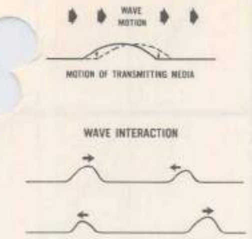
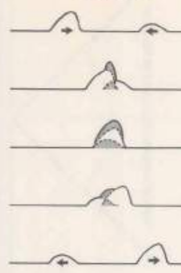
WAVE PROPAGATION



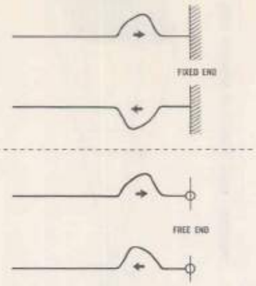
A

INTERACTION OF PULSES - SUPERPOSITION -



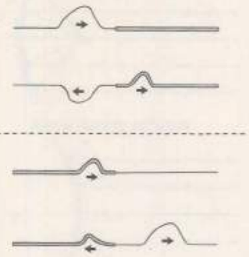
B

WAVES AT A BOUNDARY



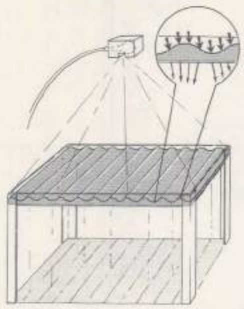
C

WAVE TRANSMISSION AND REFLECTION



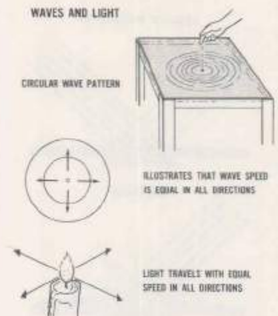
D

WAVES IN TWO DIMENSIONS



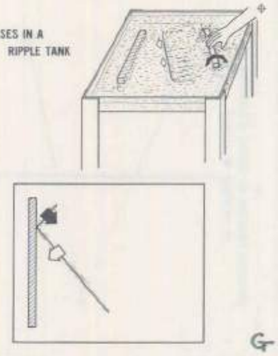
E

WAVES AND LIGHT



F

PULSES IN A RIPPLE TANK



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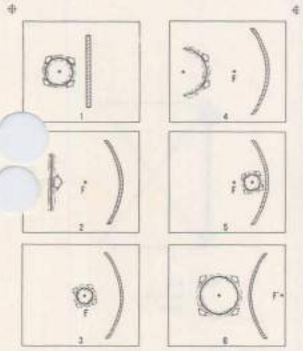
H



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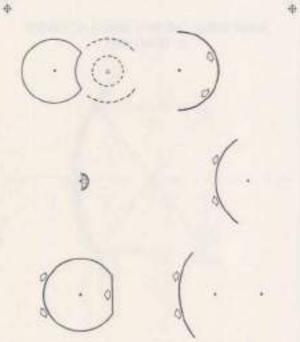
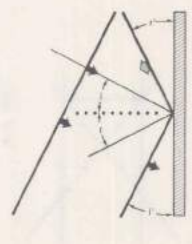


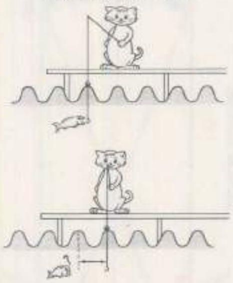
J

LAW OF REFLECTION



K

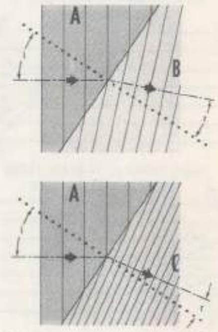
ORIGIN OF THE WAVE EQUATION



SPEED = DISTANCE / TIME = WAVE LENGTH / PERIOD = (WAVE LENGTH)(FREQUENCY)

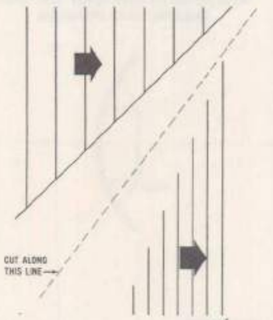
L

REFRACTION



M

REFRACTION, A FUNCTION OF WAVE LENGTH CHANGE



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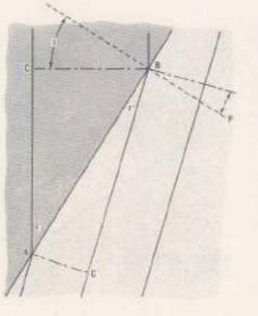
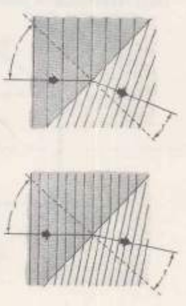


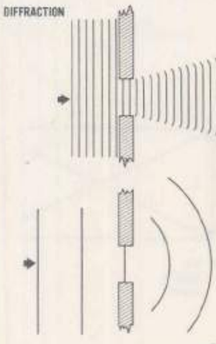
O

DISPERSION



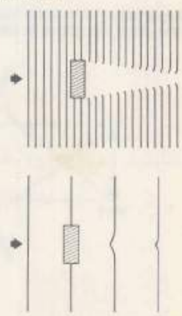
P

DIFFRACTION



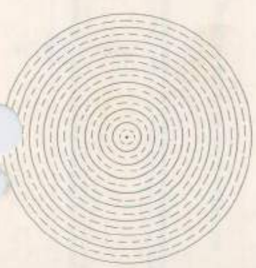
Q

DIFFRACTION



R

INTERFERENCE



S

INTERFERENCE
1/2 PHASE LAG

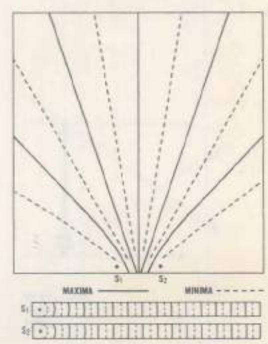
T

INTERFERENCE
3/4 PHASE LAG

U

INTERFERENCE
1/4 PHASE LAG

V



W

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PHYSICS — WAVES

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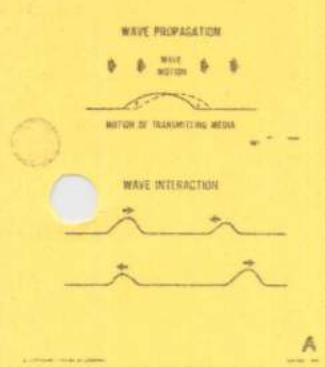
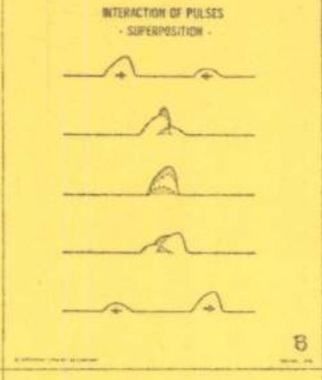
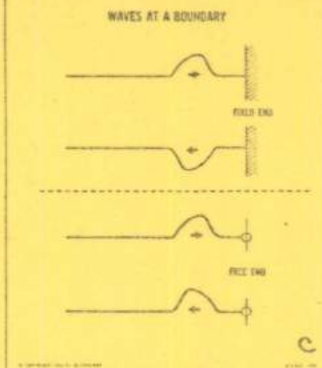
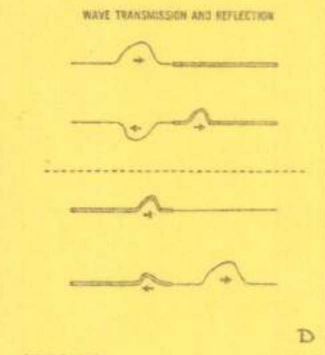
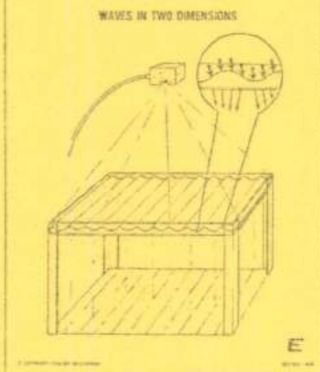
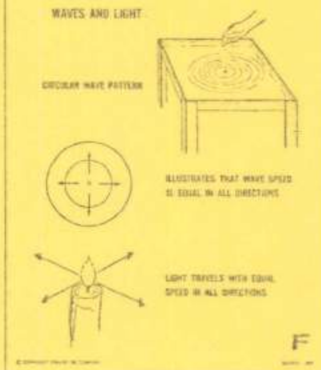


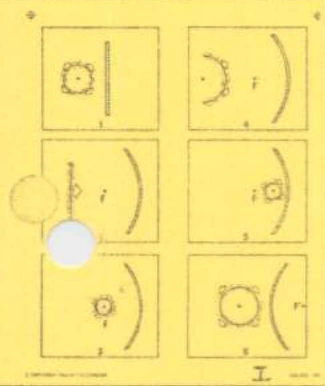


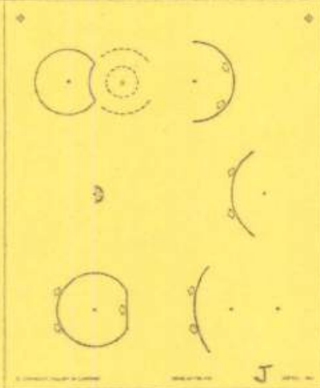


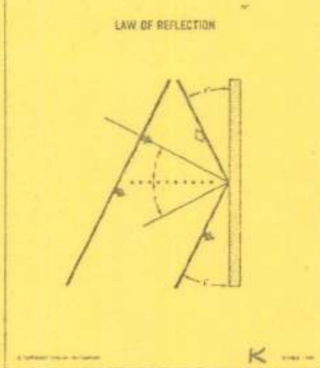


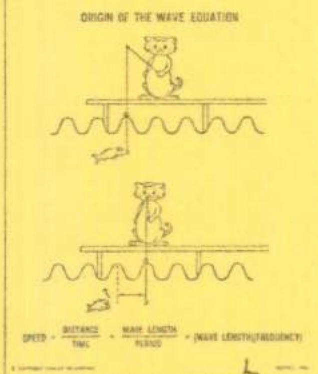


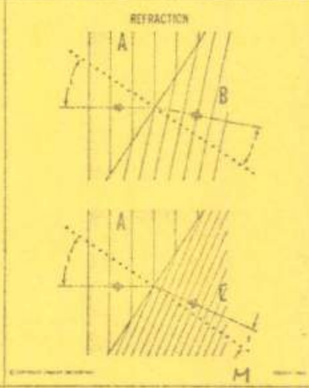


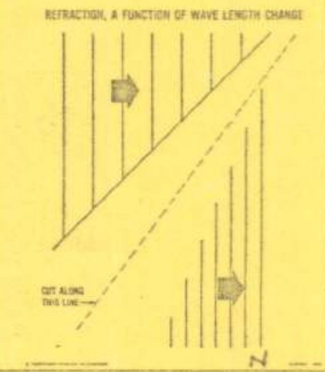


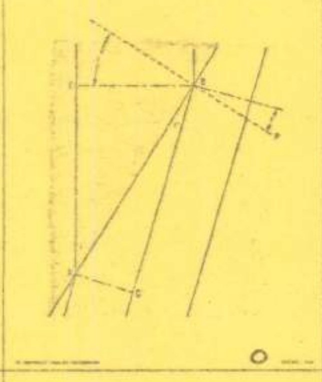


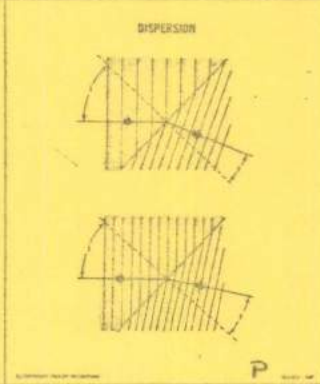


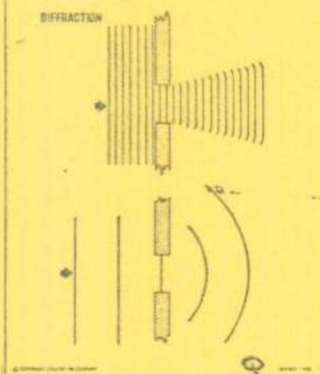


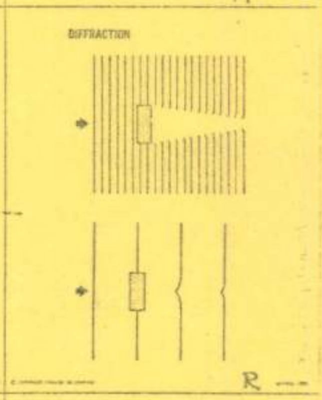


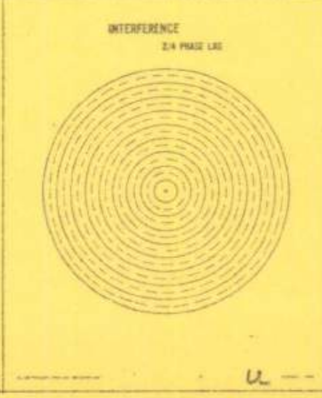


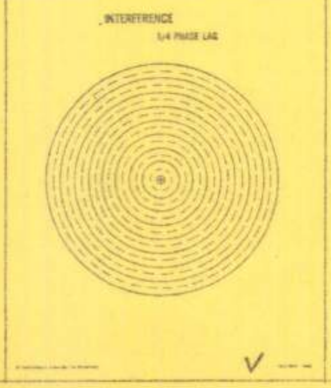


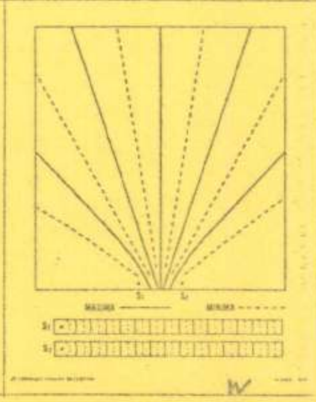












CHAPTER 23 PULSES IN A RIPPLE TANK

Set up the ripple tank. Level the tank using a circular level supplied by your instructor. Place cardboard squares under the legs, taping the squares to the counter top when the tank is level. Fill the tank with water to a depth of 5-mm to 7-mm. Place a piece of large white paper under the tank which will act as a screen to view the image of what happens in the ripple tank. Next, adjust the light source so that it acts as much like a point source as possible. Finally place the cloth covered metal strips on three sides of the tank. These will absorb excess wave energy preventing unwanted reflections. Be sure to remove these and any other item from the tank at the end of each class session. [If the tank is set up when you first encounter it, you only need to check to see if it is level.]

Hold an eye dropper near the water surface near the center of the tank and generate a pulse by allowing one drop of water to strike the surface. Observe the image of the pulse on the screen. If it is not clearly defined, you may have to readjust the lamp. Describe the pulse. From its shape, what may be inferred about the speed of the pulse in all directions?

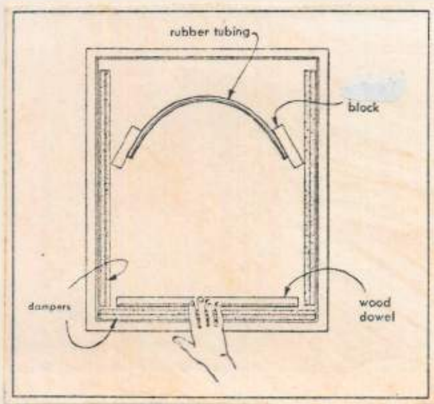
A piece of wood dowel placed parallel to one side can be used to produce a straight pulse by quickly rolling it a fraction of a revolution toward the opposite side of the tank. Describe the pulse. If the dowel is moved too slowly, the pulse will be too weak to show up well. If it is moved too rapidly, the ends of the pulse will be curved. Practice making straight pulses until you can make ones that give good images on the screen. Do the pulses remain straight as they move along the tank?

Place a straight barrier in the tank. A piece of wood, or several wax blocks may be used. Generate a pulse that will move perpendicular to the reflector. In what direction does the pulse reflect?

Repeat for various angles of incidence. Compare the angle of incidence to the angle of reflection. Have instructor verify that the proper angles were used. What relationship between the angle of incidence and the angle of reflection was determined? A number of comparisons should be made.

Reflect a circular pulse from a straight barrier. Locate the virtual source of the reflected pulse. How would you explain the reflected wave?

Substitute a length of rubber tubing for the straight reflecting barrier. Bend the tubing in the form of a parabola using the wood and/or wax blocks as shown at the right. Reflect a straight pulse from this surface. What is the shape of the reflected pulse? Find the point where the reflected pulses run together. What happens to the pulse after it converges at this point? At this point start a pulse with a drop of water. What is the shape of the reflected pulse? Try to follow the motion of several small segments of the wave fronts. How would you indicate the direction of motion of each segment? Allow drops of water to make pulses at other points. What did you observe?



Place a wooden shaped ellipse in the tank. Lower the water level until it is just below the top of the wood. Reflect circular pulses from various points. What patterns are formed? What pattern was seen when the circular pulse originated at the focus of the parabola? How would you explain this pattern?

CHAPTER 23 PERIODIC WAVES

The relation $v = f\lambda$ for the speed, frequency, and wavelength of a periodic wave holds for all periodic waves. We shall now apply this relation to waves in a ripple tank.

Check the ripple tank making sure that it is level. Obtain a green power source, straight wave generator and two connecting wires. Plug the wires into the D.C. (red and black) outlets and connect them to the generator. Place the generator into the tank making sure that the wave generator bar (the ruler) is parallel to and just touching the water. The water should be from 5-mm to 7-mm deep.

Plug in the power source, adjust the rheostat dial to read zero and then turn on the power source (red light should be on). Adjust the rheostat until the generator creates a wave pattern. It may require some experimentation with the wave generator before you are able to generate waves which show up well on the screen. (Many generators give clear waves when the power source is connected in such a way that the motor shaft rotates in the direction opposite to the motion of the wave.)

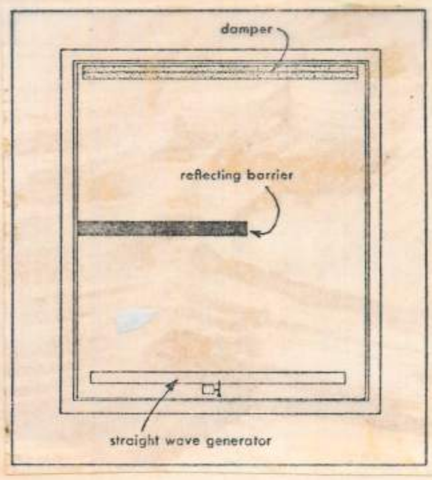
Adjust the wave generator to a low frequency. Look at the projected wave pattern through a hand stroboscope. Have your partner help you measure the frequency of rotation of the stroboscope while you "stop" the waves. How is this frequency related to that of the waves?

With the wave pattern "stopped", have your partner place two rulers parallel to the waves several wavelengths apart. Determine the wavelength of the projected waves. (The distance between one bright bar and the next.) Calculate the speed of propagation using the relation $v = f$. For best results it is necessary that the frequency of the wave remain constant while the frequency and wavelength are measured. How well did you do? Have instructor demonstrate a way to approximate the velocity of a wave so that you can evaluate you results.

Now make several measurements of the wavelength for different frequencies and determine the velocity of the waves. How accurate is your determination of the velocity?

How do the wavelength of the waves, as projected on the screen compare to the wavelength of the waves in the tank? To find out, you must determine the "scaling factor". How did you do this? How do the frequencies of the waves in the tank compare to the frequency seen on the screen?

Place a barrier in the middle of the tank as shown at the right. Adjust the frequency until a stationary pattern is produced by the superposition of the incident and reflected waves. This is called a standing wave. Compare the distance between two adjacent bright bars in the standing wave to the wavelength of the traveling wave. Conclusion?



Increase the depth of water to about 2-cm and measure the speed of the projected wave. Be careful not to change the relative position of the light source, tank and screen. How is the speed related to the depth?

SUPPLEMENT TO CHAPTER :
THE SPEED OF WATER WAVES

The following material is not presented as suggestions for extending classroom or laboratory discussions. It is intended only to serve as an aid to the teacher in answering questions and in planning laboratory programs.

For any single liquid, the speed of a surface wave depends in a complex way on the frequency of the waves and the depth of the liquid.

The speed of surface waves can be simply calculated only if:

(1) There is negligible viscosity (and therefore negligible energy loss) in the liquid.

(2) The waves are generated without turbulence (the motions in the liquid must be "simple and smooth").

(3) The amplitude, A, of the wave is much less than either the wavelength or the depth of the liquid.

If any of these factors — the viscosity, the turbulence, or the wave amplitude — becomes significant, it is extremely complicated to handle the speed theoretically.

Fortunately, all of these effects are usually negligible in ripple tanks, and the analytic formulas are close approximations to experimental results. The main cause for discrepancies between experimental observations and the theoretical descriptions which follow stems from wave amplitudes which are not negligible with respect to the wavelengths. If the wave amplitude is as much as 7% of the wavelength, the speed increases by about 10% of the wave's "small amplitude" speed. Although such an amplitude is commonly used in much of the ripple tank work, it will not affect the students' observations of various wave phenomena. It may explain some of the variations found with different wave generators. It will surely produce differences between precise experimental measurements and the values given below.

The following formulas are all derived for waves of negligible amplitude.

If the water is deep enough (a depth of $\frac{1}{2}\lambda$ will introduce less than a 1% error), the speed, v, depends on the sum of two terms as follows:

$$v^2 = \left(\frac{gv}{2\pi f} + \frac{2\pi f T}{v\rho}\right),$$

where g is the acceleration due to gravity
f is the frequency of the wave
T is the surface tension
ρ is the density.

For water, if v is to have the units of cm/sec, the following values should be used for the constants:

$$g = 980 \text{ cm/sec}^2, \qquad \rho = 1 \text{ gm/cm}^3,$$

and

$$T = 72.8 \text{ dynes/cm (or } 72.8 \text{ ergs/cm}^2).$$

Using these values, for waves in water we have for the speed v:

$$v^2 = \left(\frac{156v}{f} + \frac{457f}{v}\right).$$

From this formula, v has a minimum when $v = 23.1$ cm/sec and $f = 13.5$ cycles/sec. For much smaller values of f, $v = 156/f$ cm/sec.

However, in this case λ is large and may become larger than the depth. In the extreme, when λ is much larger than the depth H, the speed depends only on H: $v^2 = gH$.

The graph below implies that for some depth between 0.4 cm and 1 cm the wave speed would be practically constant at about 23 cm/sec, even though f varies from one cycle per second to 10 cycles per second. On the other hand, this nondependence of v on f (i.e., this freedom from dispersion) comes at the expense of a sensitivity of v on H, and H must be kept quite constant for v to be uniform.

For frequencies much higher than 13.5 cycles per second, the speed is given by:

$$v^3 = 457f \quad \text{or} \quad v = 7.7f^{1/3}.$$

Although these approximate formulas are helpful in getting a qualitative idea of the speed of water waves at various extremes of frequency, they are not adequate for predicting the detailed behavior of ripple tanks because intermediate frequencies and relatively shallow depths are used. The complete formula, including the effect of water depth, is

$$v^2 = \left(\frac{g\lambda}{2\pi} + \frac{2\pi T}{\lambda\rho}\right) \tan\text{h}\left(\frac{2\pi H}{\lambda}\right)$$

or

$$v^2 = \left(\frac{gv}{2\pi f} + \frac{2\pi f T}{v\rho}\right) \tan h \left(\frac{2\pi f H}{v}\right),$$

where tan h stands for the hyperbolic tangent.

$$\tan h\,(x) = \frac{e^x - e^{-x}}{e^x + e^{-x}},$$

For x large, tan h (x) tends toward 1.
For x small, tan h (x) tends toward x.
For water: $v^2 = \left(156\lambda + \frac{457}{\lambda}\right) \tan h \left(\frac{2\pi H}{\lambda}\right)$,
where the distances, λ and H, are in centimeters and the speed is in centimeters/second.

The graph on the following page gives a series of curves showing the velocity (in centimeters/second) of surface waves on water as a function of frequency (in cycles/second). Each curve applies to a depth, H, of the water.

The following features of the graph and formulas are of particular interest in planning ripple-tank experiments.

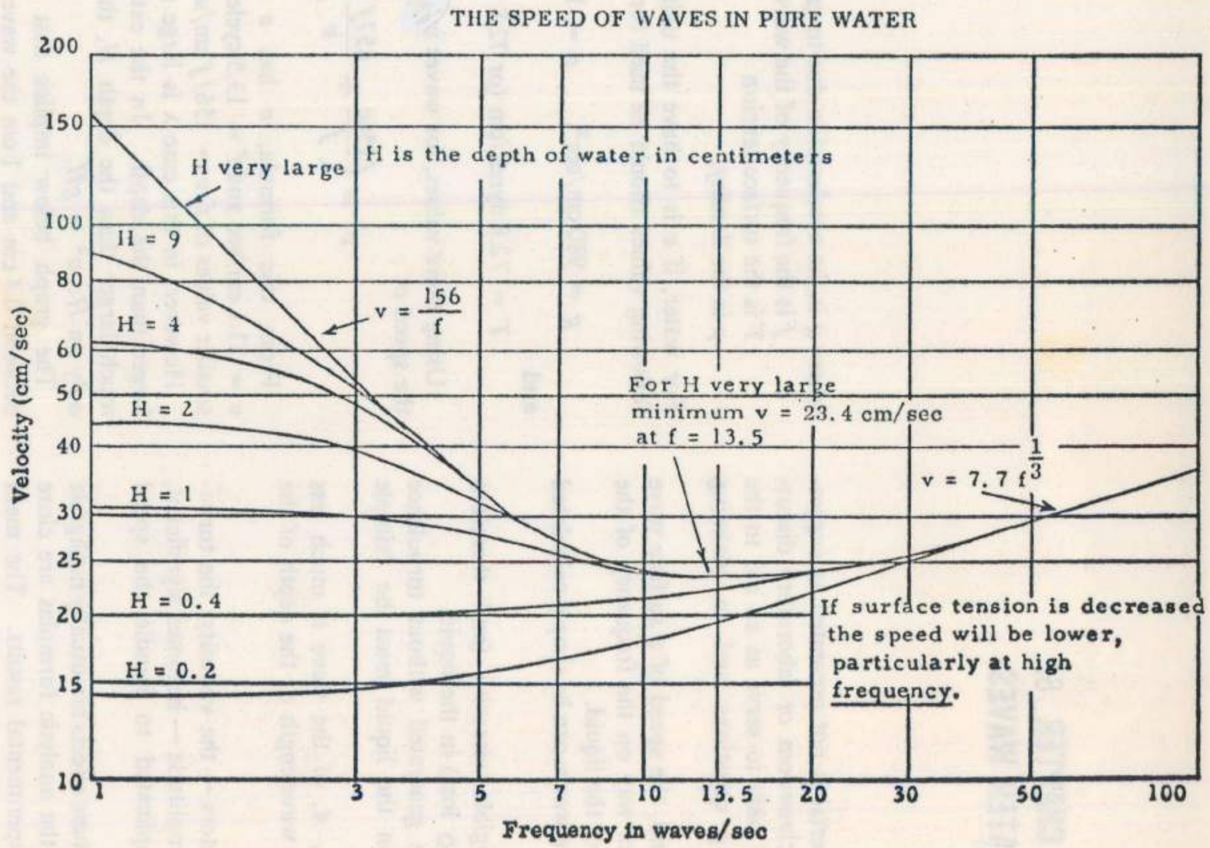
(a) *In order to minimize dispersion* (i.e., the dependence of speed on frequency), the depth of water should be small. You can choose a value suited to the frequency range you expect to use. For example, if you were interested in the range from 2 cycles per second to 10 cycles per second, $H = 0.5$ cm or 0.6 cm would be particularly good. If you wanted to use frequencies from 7 cycles per second to 20 cycles per second, $H = 0.9$ cm might be somewhat better.

(b) *In order to demonstrate refraction well,* the speed should depend strongly on depth. For this purpose, low frequency waves show a much bigger effect than higher frequency waves.

Usually, best refraction results were obtained when the shallow region was about as shallow as can be conveniently produced. Remember that when you try to get a large, extremely shallow region, it is quite difficult to keep the shallow depth uniform. If you do not keep it uniform, however, you will get a strange "beaching" effect (Figure 16–24).

(c) For other applications, the optimum depth of water in a ripple tank depends in a very complex way on the detailed shape of the waves. If the waves were pure sine waves, they would involve only a single frequency and dispersion would be unimportant. However, the periodic waves almost always contain higher harmonics, and single pulses always contain a large spectrum of frequencies. The way in which dispersion affects an actual pattern will depend on the relative amounts of different frequencies present and the ability of such waves to focus light on the screen. The only practical way to choose is to experiment. If a wave pattern is not clear, you may adjust the amplitude of the wave, the position of the screen, the details of the wave generator, or the depth of the water.

(d) For relatively low frequencies, *the surface tension* will not be too important. However, for high frequencies a very small quantity of detergent can reduce the surface tension by a large factor, thereby reducing the speed.



CHAPTER 23 REFRACTION OF WAVES

In the last experiment you found that the speed of water waves depend on the depth of water. In the range you are working, as the depth increases the speed increases. This is most apparent at low frequencies of 5-10 cps. Two different depths of water therefore constitute two different media in which waves can be propagated. This suggests that water waves can be refracted by allowing them to travel from deep water into shallow water. What do you predict as to the direction of bending of the waves as it passes from deep to shallow water? What will happen to the wavelength? How about the frequency?

To find out we must first check to see if the tank is level. Next, support a glass plate on three (3) metal rings obtained from your instructor. The glass plate should be in the center of the tank with a long side parallel to the straight wave generator. Add water to the tank until the glass plate is covered. Turn on the generator and adjust it until a low frequency wave is produced. Using a rubber hose and plastic jug, siphon water from the tank until there is a noticeable observed difference in the wavelengths in the two depths. The depth of the water over the glass plate should be 2mm or less. How does the wavelength in the shallow region compare to that in the deep region? What about the frequency? Use a hand stroboscope to check the frequency.

Turn the wave generator so that the generated waves are no longer parallel to the glass plate. Are the refracted waves straight? Still using a low constant frequency, examine the direction of propagation of the waves in the deep and shallow region. How do these directions compare? To do this, measure the angle of incidence and the angle of refraction in the deep and shallow regions respectively. Do this for several different angles of incidence. Measure several wavelengths in the deep and shallow regions. How do the wavelengths in the two regions compare? What about their speeds?

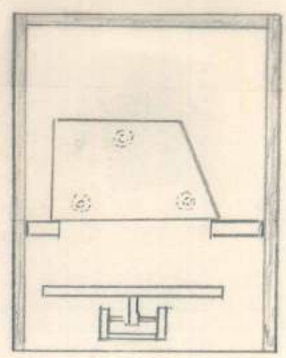
Snell's law for the refraction of light suggests that the ratio of the sine of the angles is constant. Is the ratio of the sine of the angles constant here? How about the ratio of the speeds?

Does a wave model agree with the refraction of light better than a particle model if we consider in which medium the speed of light is greater?

Start the wave generator and adjust it so that it produces waves of very low frequency. Turn the generator so that the generated waves are not parallel to the glass plate. While keeping the incident wave direction constant, slowly increase the frequency while observing the refracted wave. What happens to the direction of the refracted wave? What does this suggest about the relationship between the amount of bending and the frequency of the wave? to the wavelength?

Optional.....

Place a double concave or a double convex shaped glass plate on the metal rings. Next place wood or wax blocks at the ends of the plates to block off waves at their ends. With the depth of the water over the plates near 1 mm or less, pass straight waves of low frequency over the glass plates. What do you observe?



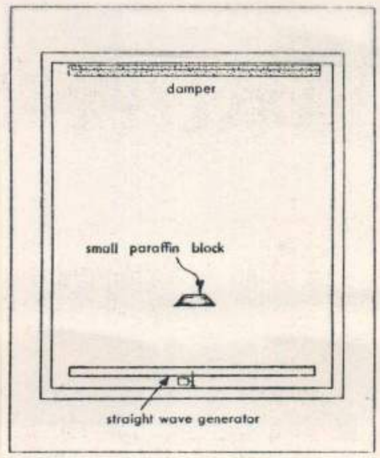
CHAPTER 23 WAVES AND OBSTACLES (DIFFRACTION)

An opaque object placed in the path of a parallel beam of light will cast a sharp shadow on a screen behind it. The shadow will be the same size as the object. What happens when we place an obstacle in the path of a straight wave?

Place the wave generator in the ripple tank which has water to a depth of 5 mm to 10 mm. Turn on the generator and make sure it can generate good straight waves over a range of frequencies. At the higher frequencies, it is essential that the generator have smooth edges. If the pattern becomes distorted at high frequencies, smooth the edge of the generator and make sure there are no bubbles on it.

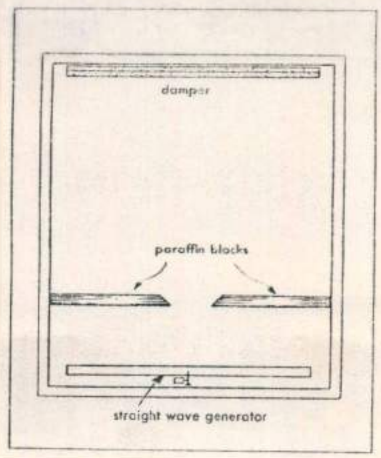
Turn on the generator and adjust for a long wavelength (low frequency). Place the end of a pencil or wood dowel in the tank in front of the generator. Does the pencil cause a "shadow" in the wave pattern of do the waves bend around it? Can you sense the presence of the pencil by observing the pattern at the end of the screen?

Stand a small paraffin or wood block in the tank as shown. Generate periodic waves of low frequency (long wavelength). What happens to the waves as they pass the block? Can you sense the presence of the block by looking at the pattern near the end of the screen? Now gradually increase the frequency. Examine the pattern as a function of the wavelength. The pattern can best be seen by looking at it through a stroboscope with all slits open. Under what conditions would you expect the block to cast sharp shadows?



We can let a parallel beam of light pass through a small opening. If a screen is held behind the opening, we shall see a light spot equal in size to the opening.

You will produce an analogous situation in the ripple tank. To do so, place a row of paraffin or wood blocks across the tank as shown. Leave a narrow opening or slit in the center. Start the straight wave generator and observe the pattern behind the slit. What happens to the pattern when you gradually change the wavelength? Keeping the wavelength constant, increase the width of the slit. What happens to the pattern? What changes in wavelength must be made to compensate for a change in the slit width?



Under certain conditions we can consider the slit to be a point source, that is the resulting pattern will be similar to that which was obtained when water was dropped into the tank from a dropper. What relation between slit width and wavelength must exist for this to be true?

Review of the Argument That Light Must Have a Very Small Wavelength

1. Water waves show reflection, refraction and dispersion.

2. Light also exhibits reflection, refraction and dispersion. Therefore, perhaps light is propagated like a wave.

3. Water waves bend at the corner of an obstacle.

4. Light casts sharp shadows. Therefore, the wave model seems to fail.

5. Do water waves always bend?

6. Not if the wave length is small. Water waves passing through a slit (or around an obstacle exhibit appreciable bending when the size of slit (or obstacle) is approximately equal to or less than a wave length.

7. Since light casts sharp shadows of ordinary objects we can conclude that <u>if</u> its propagation is wave-like, <u>then</u> its wave length must be much smaller than the size of these objects. To verify this possibility will require experiments with small slits and obstacles to find out if bending occurs.

8. Experiment shows that for sizes less than 1/10 millimeter, bending of light occurs.

9. Thus, rather than demonstrating a failure of the wave model, preliminary investigation of diffraction effects provides corroboration of a prediction suggested by the wave model. This must be viewed as strong support for the wave point of view.

In this argument, we use tangible water waves as a model to explore the possible nature of light. When we infer properties of light from observation of ripples in a tank, we are making a large extrapolation, which <u>must be tested by an experiment with light</u>. Thus, the observation of the bending of water waves, by itself, does not <u>prove</u> that light bends any more than the fact that we can hold water in a bucket proves that we can hold light in a bucket. However, in this case, our model gives us the key to the proper experiment with light, by pointing up the importance of the quantity λ/d in determining the amount of bending.

STUDY NOTE: Units for Frequency

"Frequency" is a funny physical quantity because of its units. Frequency is defined as the rate at which some repetitive phenomenon goes through successive complete cycles. For example, a wave with a frequency of 10 cycles per second goes through 10 complete repetitive motions every second. If you take a flash photograph of the wave at some time and see the wave with a particular shape, you will find that the wave reassumes that shape 10 times during every second.

You would then logically deduce that the correct physical units attached to quantities of frequency are cycles/time. This is indeed correct, but in doing algebraic manipulations involving frequencies, you must be careful or else things won't appear to come out right. Suppose a wave has a frequency of 10 cycles per second and a wavelength of 10 cm. When you calculate the wave velocity using the formula, $v = f\lambda$, you get the result $v = 100$(cycles X cm/sec). Clearly,(cycles X cm/sec) are funny units for velocity, but it turns out that this just shows a lack of completeness in labeling the wavelength. Wavelength is a specific length per cycle, but in writing it, scientists usually give the value just in terms of length (and assume that it is understood that the appropriate unit is length/cycle). If in our example we say λ(wavelength) is 10 cm/cycle, then our wave velocity formula yields:

$$v = (10 \text{ cycles/sec}) \times (10 \text{ cm/cycle})$$
$$= 100 \frac{\text{cycle - cm}}{\text{sec - cycle}} = 100 \text{ cm/sec}$$

The "cycle" units cancel out and we are left with $v = 100$ cm/sec --a correct set of units for velocity. As you use the concept of frequency in working out exercises, remember the "unlisted" part of the wavelength units (length per cycle).

Physicists have invented a special, concise unit for frequency called the Hertz (Hz) after the German physicist who first produced and detected radio waves. One hertz is defined as one cycle per second. Very often you will see radio stations listing their frequency in Hz--you can translate this directly in cycles per second.

Chapter 23 Written Exercise

1. A point source in a ripple tank vibrates 8.3 times per second. With a stroboscope, we stop the motion of the wave, and measuring we find the difference between the radii of the first and sixth circular crests to be 12.0 cm. (a) What is the wavelength? (b) What is the velocity of the wave?

a. ______________

b. ______________

2. A straight wave passing from a shallow to a deep section of a ripple tank makes an angle of incidence of 45° and an angle of refraction of 60°. If the frequency of the wave is 4.5/sec and its speed is 25 cm/sec in the deep part of the tank, (a) what is the speed in the shallow part of the tank?
(b) What is the wavelength in the shallow part?
(c) What is the wavelength in the deep part?

a. ______________

b. ______________

c. ______________

3. Assuming that sound is a wave phenomenon (it is), explain why a high-fidelity sound system needs only one low-frequency speaker, but must have several high-frequency speakers pointing in different directions.

Chapter 23 - Written Exercise

1. A point source in a ripple tank vibrates 8.3 times per second. With a stroboscope, we stop the motion of the wave, and measuring we find the difference between the radii of the first and sixth circular crests to be 12.0 cm. (a) What is the wavelength? (b) What is the velocity of the wave?

a. 2.4 cm

b. 19.9 cm/sec

2. A straight wave passing from a shallow to a deep section of a ripple tank makes an angle of incidence of 45° and an angle of refraction of 60°. If the frequency of the wave is 4.5/sec and its speed is 25 cm/sec in the deep part of the tank, (a) what is the speed in the shallow part of the tank? (b) What is the wavelength in the shallow part? (c) What is the wavelength in the deep part?

a. 20.4 cm/sec

b. 4.54 cm

c. 5.56 cm

Shallow		Deep
45°	θ	60°
4.5/sec	f	4.5/sec
	v	25 cm

$$\frac{v_d}{v_s} = \frac{\sin\theta_d}{\sin\theta_s}$$

$$\frac{v_d'}{v_s} = \frac{\sin 60^{\circ}}{\sin 45^{\circ}}$$

3. Assuming that sound is a wave phenomenon (it is), explain why a high-fidelity sound system needs only one low-frequency speaker, but must have several high-frequency speakers pointing in different directions.

A. Pulses in a Ripple Tank

1. Allow water drops to hit water
2. Generate straight pulses
3. Reflect straight pulses from straight barriers
4. Vary the angle of incidence
5. Reflect circular pulses from straight barriers
6. Reflect straight pulses from parabolic barrier
7. Water drop at principle focus
8. Water drop at other than principle focus
9. Wooden shaped ellipse

B. Periodic Waves

1. Determine frequency of wave
2. Measured frequency vs actual frequency
3. Determine wavelength
4. Determine speed, have checked
5. Speed for various frequencies
6. Actual vs measured wavelength
7. Standing Waves
8. Speed at greater depth

C. Refraction of Waves

1. Measurements of angles in deep and shallow
2. Wavelength in deep and shallow
3. Sine angle in deep/sine angle in shallow
4. Speed in deep/speed in shallow
5. Dispersion

D. Waves and Obstacles

1. Pencil in path of low frequency waves
2. Block in path of low frequency waves
3. Narrow slit- vary frequency(wavelength)
4. Increase slit width
5. Slit width vs wavelength -pattern relationship

— Over —

EXPERIMENT II - 7 PULSES IN A RIPPLE TANK

DEPTH H_2O 1/2 TO 3/4 CM IN LEVEL TANK

How do you know?

1. TOUCH H_2O WITH FINGER.
   1. WHAT IS SHAPE OF PULSE?
   2. IS SPEED OF PULSE THE SAME IN ALL DIRECTIONS? shape tells you
2. USE WOOD DOWEL TO MAKE STRAIGHT PULSES.
   1. DO PULSES REMAIN STRAIGHT?

* LET END OF TANK OR PARAFFIN BLOCKS ~~AS~~ BE STRAIGHT BARRIER.
1. GENERATE STRAIGHT PULSE. ∠i = 0
   1. IN WHAT DIRECTION DO THEY REFLECT?
2. USE VARIOUS ∠i 's.
   1. ARE REFLECTED PULSES STRAIGHT?
   2. *→ HOW DOES ∠r compare to ∠i? NEED MEASUREMENTS*

* USE MEDICINE DROPPER TO MAKE CIRCULAR PULSE.
1. REFLECT CIRCULAR PULSE FROM STRAIGHT BARRIER.
   1. WHERE IS VIRTUAL SOURCE?
   2. HOW WOULD YOU EXPLAIN THE RESULT?

USE PARAFFIN BLOCKS TO SHAPE RUBBER TUBING.
1. REFLECT STRAIGHT PULSES FROM PARABOLIC RUBBER TUBING
2. FIND AND MARK FOCUS OF PARABOLA ON SCREEN
   1. HOW INDICATE DIRECTION OF MOTION OF EACH SEGMENT?
   2. HOW DOES THIS RELATE TO LIGHT RAYS?
   3. ARE RAYS REPRESENTING INITIAL DIRECTION ‖ TO EACH OTHER?

USE MEDICINE DROPPER TO MAKE CIRCULAR PULSE.
1. GENERATE CIRCULAR PULSES AT FOCUS OF PARABOLA.
   1. WHAT IS SHAPE OF REFLECTED PULSE?
   2. ARE THERE OTHER PLACES WHICH GIVE SAME RESULT?
   3. HOW MUST ∠r COMPARE TO ∠i HERE?

NEW *

Important
Use low frequencies

EXPERIMENT II - 8 PERIODIC WAVES

* USE "MY" STRAIGHT WAVE GENERATOR. EXPLAIN H_2O $\frac{1}{2} \to \frac{3}{4}$ cm

1. PRACTICE USING AT VARIOUS FREQUENCIES
    1. HOW CAN YOU GET A CLEAR IMAGE?
2. USE STROBE TO OBSERVE (2 OR 4 SLITS)

* USE LOW FREQUENCY [BE SURE IT IS CONSTANT]

1. * 1. MEASURE FREQUENCY OF STROBE [AT HIGHEST FREQUENCY]
    2. RELATE TO FREQUENCY OF WAVE.

USE TWO RULERS, STROBE

2. 1. DETERMINE λ OF WAVES [USE SEVERAL λ]
    * 2. HAVE EACH PARTNER USE STROBE FOR EACH READING.
3. 1. HOW ACCURATE IS YOUR DETERMINATION OF SPEED?
4. 2. HOW IS APPARENT λ RELATED TO TRUE λ?

* ADDITIONAL: FOUR (4) more TRIALS [measure f, λ, calculate v]

5. PLACE BARRIER IN MIDDLE OF TANK [PRODUCE STANDING WAVE]
    1. HOW DOES DISTANCE BETWEEN 2 BRIGHT BARS COMPARE? WITH STANDING + TRAVELING WAVE?
    2. CAN YOU MEASURE λ IN STANDING WAVE?

CHANGE DEPTH OF H_2O CONSIDERABLY (2 cm)

1. CAN YOU DETECT CHANGE IN SPEED?

* 1. NEED EXPERIMENTAL EVIDENCE. [f, λ] [CALCULATE v]

DEMONSTRATION

1. STANDING WAVE IN SPRING [measure λ, f; CALCULATE v]
2. PRODUCE OTHER STANDING WAVES [same length]
3. DO NOT HAVE TWO DIFFERENT SPRINGS: Various MATERIAL

EXPERIMENT II - 9 REFRACTION OF WAVES

FROM II-8 v DEPENDS ON DEPTH H_2O

GLASS PLATE ≥ 1.5 CM ABOVE BOTTOM OF TANK. [LEVEL]

H_2O ≤ 0.2 CM OVER GLASS PLATE [DEPTH H_2O UNIFORM]

1. WHAT DO YOU PREDICT IF STRAIGHT PERIODIC WAVE CROSSES INTO SHALLOW H_2O? ∠i = 0

1. USE LOW FREQUENCY TO TEST PREDICTION [USE STROBE]

* CHANGE ∠i MOVING EITHER GLASS OR GENERATOR
    1. ARE REFRACTED WAVES STRAIGHT?
    2. HOW DOES ∠r COMPARE W/ ∠i
    3. HOW DO λ IN TWO SECTIONS COMPARE?
    4. WHAT ABOUT SPEEDS?

KEEPING GENERATOR RUNNING [f CONSTANT]

1. CHANGE ∠i AND COMPARE AS ABOVE
    1. DOES WAVE MODEL AGREE W/ REFRACTION BETTER THAN PARTICLE MODEL? COMPARE v's

USE CONSIDERABLE CARE.

OVER WHAT RANGE SHOULD YOU CHOOSE ∠i?

WHAT DO YOU CONCLUDE FROM YOUR RESULTS?

Experiment II-10 Waves and Obstacles

Place Small Smooth Paraffin Block 10 cm from Barrier

A. Use long λ.

1. Do waves continue straight path on both sides? NOT IF $\lambda \geq \frac{1}{2}$ obj…
2. Could you sense blocks presence on screen? (NO)
3. Does block cast sharp shadow? (NO)

B. Reduce λ (increase f) Observe with Strobe

1. How is pattern changed behind block? (SHARPER)
2. Under what conditions do you expect sharp shadow?

discuss using λ !

Use Paraffin Blocks to Make Opening (of width d)

A. Use long λ

1. Are they straight behind slit? (NO)
2. Do waves move in original direction?

B. Decrease λ

1. What happens? (straighten)

C. Change width "d" (use medium λ)

1. How adjust λ to compensate pattern change?

angle of bending depends on λ/d

Test Chapter 23

Name____________________

Date________________

1. Figure 1 shows an incident straight pulse approaching a long straight barrier at an angle. Show accurately (by construction) the direction and position of the pulse as it just reaches point X on the barrier. Label and measure the angles of incidence and reflection on the diagram.

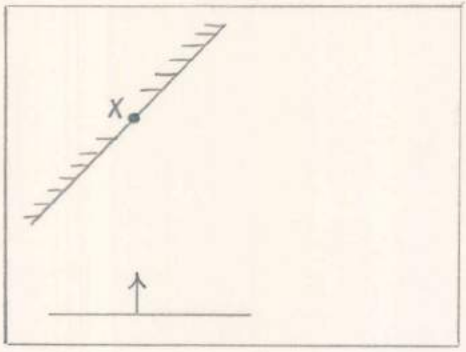


Figure 1

2. Using Figure 2, prove:

   a. $\frac{\sin i}{\sin r} = \frac{\lambda_1}{\lambda_2}$

   b. $\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$

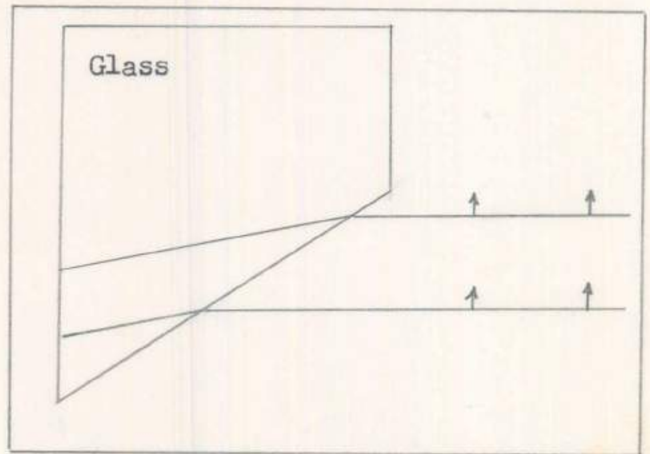


Figure 2

Ripple tank with water over glass (two depths) to show refraction.

3. Periodic straight waves in a shallow area of a ripple tank are incident at an angle of 40° to a deep area of the water. The frequency and wave length of these waves are respectively 10 cycles per second and 1.4 cm long.

   a. What is the velocity of the waves in the shallow area of the water?

   b. What is the velocity of the waves in the deep region of water, if the angle of refraction in the deep region is 64°?

4. Figure 3 shows a circular pulse, at time t_1, moving outward from its source, point A, toward the barrier. If the pulse can travel the remaining distance to the barrier in the time interval Δt, show the shape and direction of motion of the pulse at time, $t_1 + 2\Delta t$.

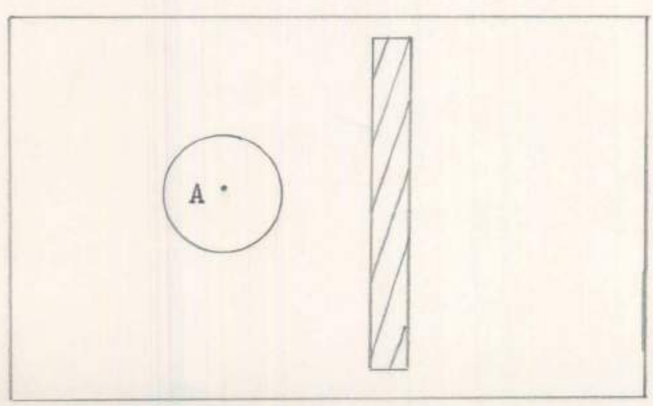
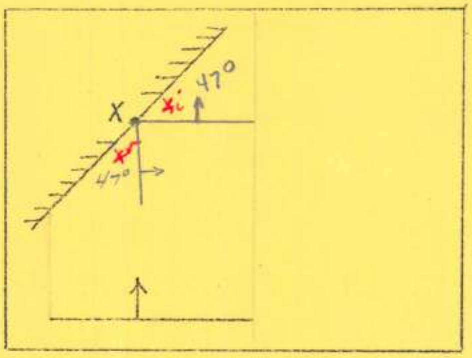


Figure 3

1. Figure 1 shows an incident straight pulse approaching a long straight barrier at an angle. Show accurately (by construction) the direction and position of the pulse as it just reaches point X on the barrier. Label and measure the angles of incidence and reflection on the diagram.

5



∢i = 47°

∢r = 47°

Figure 1

2. Using Figure 2, prove:

3

a. $\frac{\sin i}{\sin r} = \frac{\lambda_1}{\lambda_2}$ $\frac{\sin 33°}{\sin 22°}$

b. $\frac{\sin i}{\sin r} = \frac{v_1}{v_2}$

a. $\frac{\sin 33°}{\sin 22°} = 1.45 \quad 1.42 = \frac{12.8\ mm}{9\ mm}$ ✓

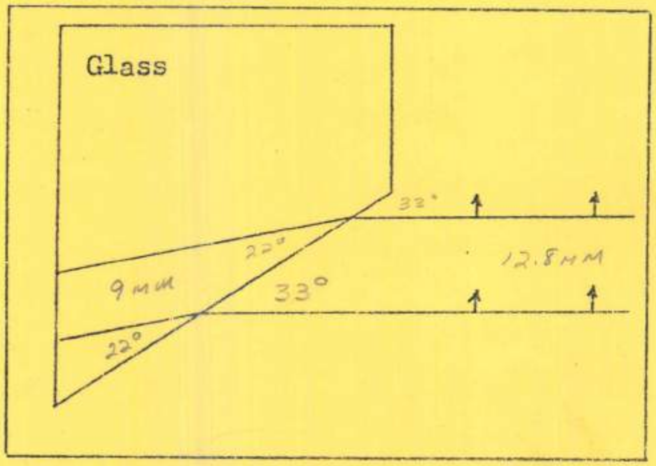


Figure 2

b. SAME AS $\frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$ ✓

Ripple tank with water over glass (two depths) to show refraction.

3. Periodic straight waves in a shallow area of a ripple tank are incident at an angle of 40° to a deep area of the water. The frequency and wave length of these waves are respectively 10 cycles per second and 1.4 cm long.

4 a. What is the velocity of the waves in the shallow area of the water?

4 b. What is the velocity of the waves in the deep region of water, if the angle of refraction in the deep region is 64°?

$\theta_s = 40°$ a. $v_s = f_s \lambda_s = 10\,\frac{1}{sec} \times 1.4\ cm = 14\ \frac{cm}{sec}$

$f_s = 10\,\frac{1}{sec}$

$\lambda_s = 1.4\ cm$

$\theta_d = 64°$

b. $\frac{v_d}{v_s} = \frac{\sin\theta_d}{\sin\theta_s} = \frac{\sin 64°}{\sin 40°} \times 14\ \frac{cm}{sec}$

$v_d = 19.6\ cm/sec$

~~in a ripple tank~~, in a ripple tank. In outline of tank

4. Figure 3 shows a circular pulse, at time t_1, moving outward from its source, point A, toward the barrier. If the pulse can travel the remaining distance to the barrier in the time interval Δt, show the shape and direction of motion of the pulse at time, $t_1 + 2\Delta t$.

4

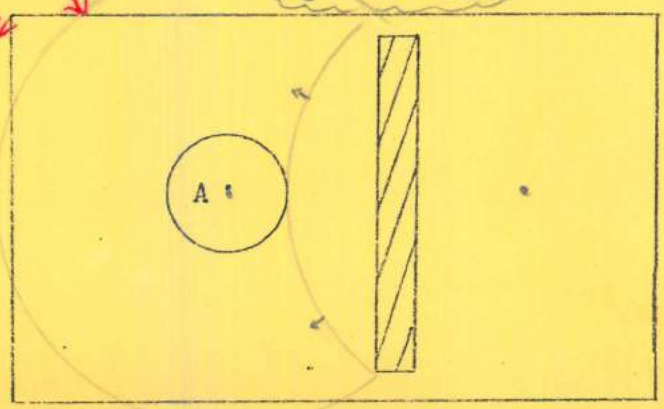


Figure 3

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