86-87

Chapter 22 INTRODUCTION TO WAVES

To this point we have discussed the reflection and refraction of light, and how these phenomena might be explained if we regard light to be composed of particles. However, a simple particle model of light is inadequate to explain the results of experiments involving the speed of light in various media. It is logical then to seek an alternative model for light, and with this goal in mind we begin a study of waves. In this chapter, we will take a look at how the behavior of a pulse on a spring is analogous in many ways to the behavior of light. This hints that a wave model for light is worth pursuing in detail. In later chapters, we will refine the wave model and discover that it predicts some properties of light which most of us ordinarily never encounter, but which can indeed be observed if we perform careful experiments.

PERFORMANCE OBJECTIVES

After completing this chapter, you should be able to

1. Generate a pulse on a slinky and predict its behavior:
   a. as it travels along the slinky
   b. when it reflects from an "open" and "closed" end.
   c. when it is transmitted to a slinky of different density.
2. Construct a (sideways displacement vs position along the slinky) graph and use the graph to calculate the sideways velocity of the slinky.
3. Use the principle of superposition to predict the resultant shape of a spring when two pulses cross.
4. Debate how the one dimensional wave model relates to the behavior of light
   a. when it is reflected
   b. when it is refracted
   c. when two or more light beams are superimposed one upon the other.

1. Read: Section 22-1 A Wave: Something Else That Travels page 449

2. Suppose you look out your window and see your neighbor across the street sitting on his porch. In how many ways could you do something to attract his attention, make him move, or otherwise influence his actions? Can the ways identified be separated into a few (how many) classes?

3. Experiment: Waves in One Dimension (Experimental Notes Provided)

   Do only Part A: Transverse Waves in a Spring

   a. Answer each question; then have evaluated by your instructor.

   b. Optional...There are two factors which govern the speed that a pulse moves along the slinky. The first is tension. Tension is the measure of the force (in Newtons) that is applied to the slinky. The second is the density of the slinky. (This is found by dividing the mass of the slinky by the length that the slinky is stretched.)

      Verify the following formula by comparing calculated with experimental values.

      $$v^2 = T/m/L$$

      T = Tension (N)
      m = mass of slinky (kg)
      L = length of slinky (m)

   c. View Film Loop: #81291 Single Pulses in a Spring (Film Notes Enclosed)

6. Problems: page 452: #1 #2 #4

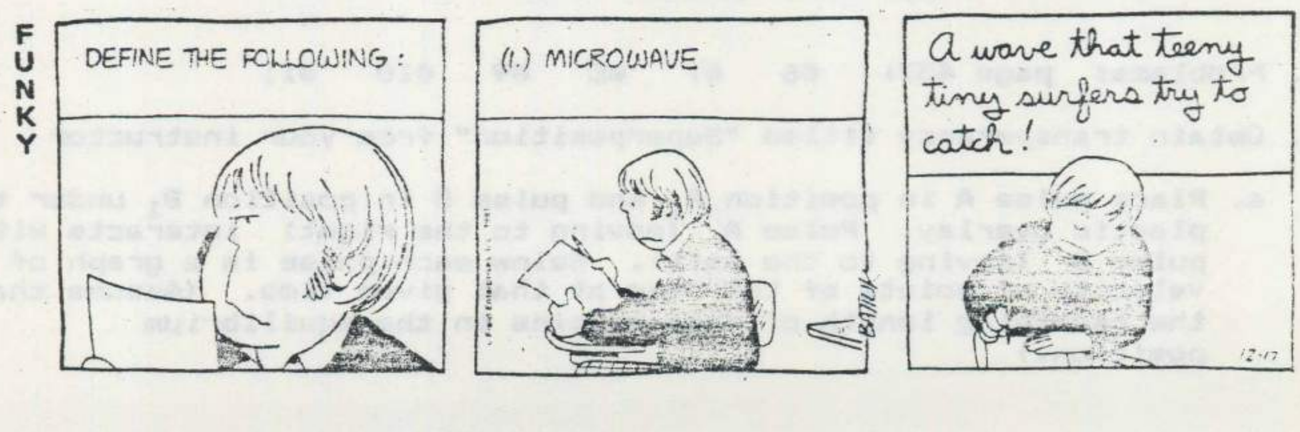
7. Read: Section 22-3 Superposition: Pulses Crossing page 453

8. Experiment: Waves in One Dimension Part B: Collision of Wave Pulses: Superposition (Experimental Notes Provided)

   a. Answer each question; then have them evaluated by your instructor.

   b. View Film Loop: #81293 Superposition of Pulses in a Spring

   c. View Film Loop: #81590 Superposition of Pulses (Computer Animated)

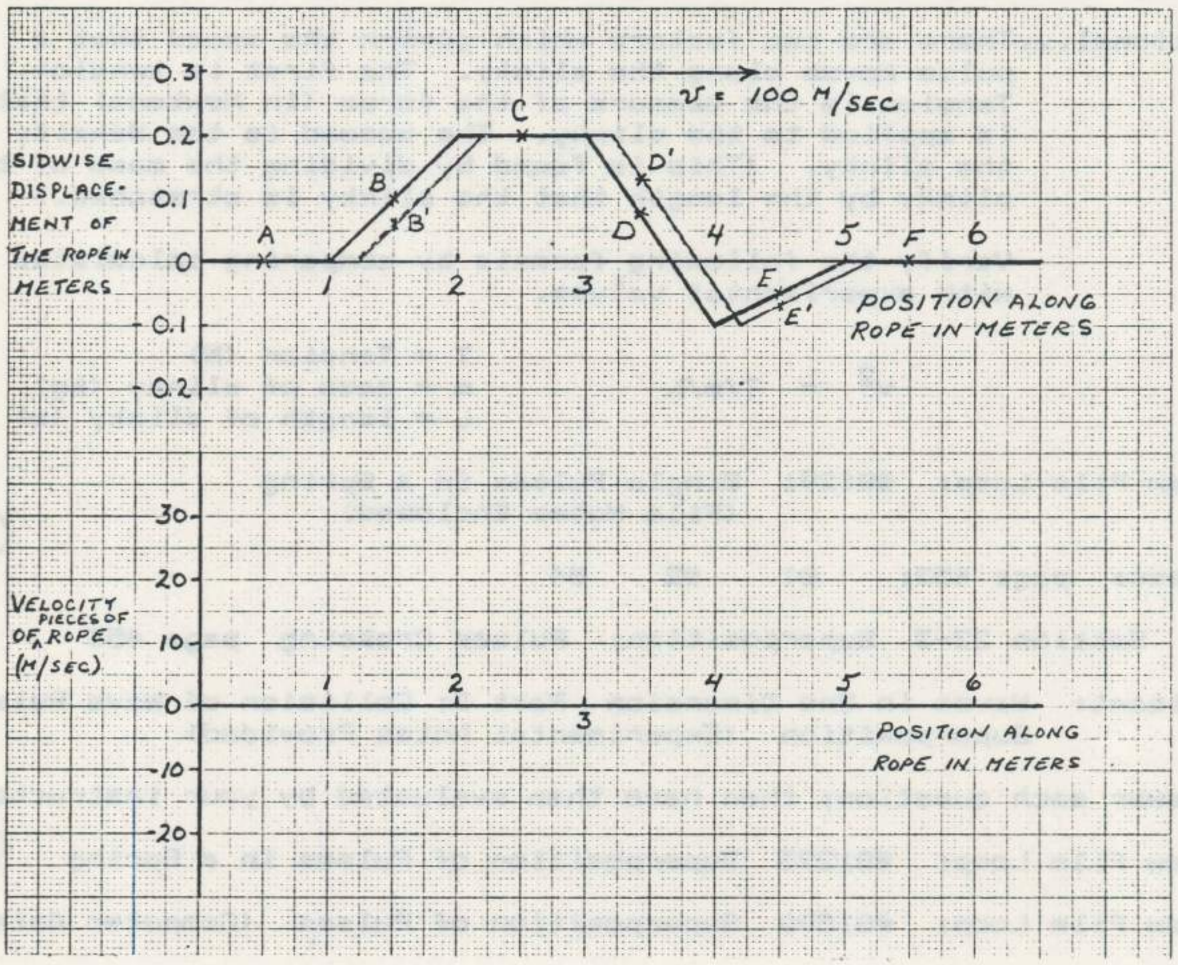


9. The graph below shows a pulse (solid line) at a given time "t". The dashed line shows the pulse 0.002 seconds later. The pulse has a velocity of 100 m/sec to the right.

   a. Of the six points (A, B, C, D, E, F), which are moving up? Down? Not moving?

   b. Which point(s) are moving fastest?

   c. Determine the velocity of each segment that is moving. Then graph the sideways velocity of the segments of the rope as a function of the position along the rope on the axis provided directly below the first graph.



10. Problems: page 457: #6 #7 #8 #9 #10 #11

11. Obtain transparency titled "Superposition" from your instructor

   a. Place pulse A in position A_1 and pulse B in position B_1 under the plastic overlay. Pulse A (moving to the right) interacts with pulse B (moving to the left). Below each pulse is a graph of velocity of points of the rope at that given time. (Assume that the remaining length of rope remains in the equilibrium position.)

b. Now move pulse A and B to A_2 and B_2 respectively. Using the principle of superposition, determine the shape of the rope at this time. Using the same principle, determine the resultant velocity of each point. You can draw on the plastic overlays using a grease pencil.

c. Repeat this procedure as A moves to the right and B moves to the left. As you complete this exercise, you should be comparing your results with Figure 22-5, page 453.

d. Repeat the above using pulse C instead of pulse B. Compare your findings with Figure 22-7, page 455.

12. Experiment: Waves in One Dimension - Part C.

a. Answer each question; then have evaluated by your instructor.

13. View the following Film Loops. (Film notes enclosed.)

a. #81294 - Transverse Wave Apparatus
b. #81296 - Transverse Standing Waves in a Spring - Wave Groups
c. #81297 - Transverse Standing Waves in a Spring - Continuous Wave Trains
d. #81295 - Reflection of Waves in A Spring - Free and Fixed End

14. Read: Section 22-4 Reflection and Transmission page 457

15. A review sheet titled "Boundary Conditions for a String" has been included for your examination. Information taken from pages 415-416 of "College Physics" by Sears and Zemansky (Third Edition).

16. Problems: page 459: #12 #13 #14 #15 #16
page 463: #20 #21 #22 #23 #24

...Note....Discuss #22 with your instructor.

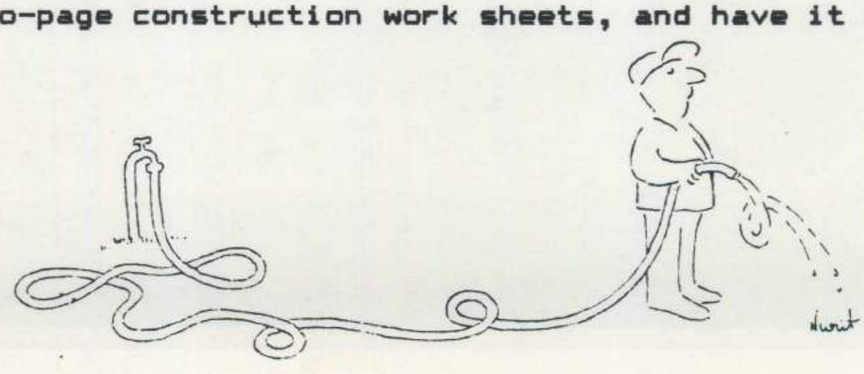
17. Read: Section 22-5 Idealizations and Approximations page 460

18. What have we learned so far from the activities of this chapter? Make a brief outline and discuss it with your partner. Your instructor would like you to share the outline with him.

19. Has your understanding of wave behavior in one-dimension been such to suggest whether or not it can be used as a model of light? How does the status of the wave behavior compare in your mind to the particle behavior model?

20. Read: Section 22-6 A Wave Model For Light? page 462

21. Complete the two-page construction work sheets, and have it evaluated.



ANSWERS CHAPTER 22

6\. (1) At the point of maximum displacement.
   (2) It would still move up first.
   (4) S.A.B.

8\. (a) regions that are not clear indicate motion
   leading edge moving up, trailing edge moving down

9\. (a) D – up   B,E – down   A,C,F – not moving
   (b) D
   (c) B = –20 m/sec   D = + 30 m/sec   E = – 10 m/sec
   Be sure to discuss with your instructor.

10\. (6) no
   (7) (8) (9) (10) (11) S.A.B.

16\. (12) (13) S.A.B.
   (14) The incidence pulse.
   (15) Three
   (16) The pulse is smaller in the bottom frames.
   (20) The speed of the pulse is less in the second coil.
   (21) S.A.B.
   (22) In springs: if moving from greater to lesser speed – reflected pulse is upside down
   From air to water, we'd expect reflected pulse to be reflected upside down.
   (23) (24) S.A.B.

NANCY

HI AND LOIS   Mort Walker and Dik Browne

TRANSVERSE STANDING WAVES IN A SPRING
*** WAVE GROUPS ***
81296

Film Summary

A pulse moving from right to left is reflected at a fixed end and becomes a pulse going from left to right. This procedure is repeated with pulses that become progressively more complex, such as a crest followed by a trough, then a wave train with two crests and two troughs. Successive pulses have increasingly greater numbers of crests and troughs. Slow motion shows what happens at the reflected end, and it is seen that during the interval when both incident and reflected waves are in the same region, the pattern is no longer that of a running wave. There are crests and troughs, but they move neither to the left nor to the right. Instead, each crest flattens out and becomes a trough which, in turn, flattens out and becomes a crest again. In other words, superposition of two waves has produced standing waves.

An experiment is performed with three long spiral springs. The top one carries waves from left to right, the bottom one carries waves from right to left, and the middle one carries waves in both directions. When the ends of the springs are vibrated in simple harmonic motion, running waves are seen in the first and third springs and a standing wave in the middle one. This is shown first at normal speed and then in slow motion.

Concepts

The main concept is that of a standing wave. Interference of two wave trains is illustrated and explains how two continuous waves going in opposite directions produce, in obedience to the principle of superposition, a wave that is stationary in space. Such a wave exhibits nodes and antinodes. Waves of the same frequency and amplitude generated simultaneously at both ends of a spiral spring can result in standing waves, but there are several instances in the film when it is clearly seen that once a wave has been started it can interfere with its reflected wave to produce standing waves. It is not necessary to have independent generators at each end of the spring.

TRANSVERSE STANDING WAVES IN A SPRING
** Continuous Wave Trains **
81297

Film Summary

One end of a long spiral spring is moved at right angles to its length in simple harmonic motion. This generates transverse waves which travel to the fixed end where they are reflected back along the spring. They begin to set up transverse standing waves. The motion of selected points on the spring, singled out by circular patches attached to it, is observed with the aid of slow motion and special lighting effects which reveal that there is essentially no motion at the nodes, and simple harmonic motion of large amplitude at the antinodes.

In another sequence individual exposures long enough to produce blurring emphasize the fact that all points except those at the nodes move in simple harmonic motions of varying amplitudes. In some sequences the frequency of the generating mechanism does not correspond to one of the natural frequencies of the spring and no clear standing wave pattern results. The film ends with successive close-ups of two of the natural modes of vibration.

Concepts

Some of the natural modes of oscillation of a spiral spring in transverse motion are produced by vibrating one end of it at the corresponding characteristic or natural frequencies. The special behavior of points at nodes and antinodes is examined with care. What we see are transverse standing waves in an approximately one-dimensional medium. Interference between incident and reflected transverse waves with common frequencies and amplitudes produces the standing waves and their corresponding nodes and antinodes by superposition.

SINGLE PULSES IN A SPRING
81291

Film Summary

A well-illuminated long spiral spring suspended in a horizontal position by thin strands of gut fish line leader is used to demonstrate pulses. For transverse pulses these strings are equally spaced and vertical. For longitudinal pulses, two strands attached at equal intervals along the spring form V-shaped bifilar suspensions.

The far end of the spiral spring is mounted in a way that damps the motion so that no disturbing reflections take place. Single transverse pulses are sent down the spring and are observed at normal speed and in slow motion. With close-ups in slow motion the camera focuses on a single spot on the spring. A round paper disk allows examination of its motion as the pulse passes by.

A similar series of shots permits study of single longitudinal pulses formed in the spiral spring first by compression and then by rarefaction. Once again a spot is singled out using a paper disk for close-up and slow observation of the details of its motion as pulses of compression and rarefaction pass by.

Concepts

A pulse is a transient motion which occurs at a certain place and time in a medium and which is later reproduced identically at another place in the same medium. The experiments show that in a pulse whatever happens here and now will happen identically elsewhere and later in the same medium.

Strictly speaking, a spiral spring is only approximately one-dimensional, but its length is so much greater than its width that the approximation is quite good for small amplitudes. The effect of a pulse on a single particle is shown in slow motion. We see that in a transverse pulse the motion is at right angles to the direction of propagation (along the spring) and that in a longitudinal pulse it is parallel to it. Other concepts presented are compression and rarefaction.

TRANSVERSE WAVE APPARATUS
B1294

Film Summary

A torsion-bar machine is used to generate waves. It consists of a long thin wire to which rods are attached at regular intervals. Each rod is at right angles to the wire and is attached at its midpoint. The wire is supported horizontally. When one of the rods is pushed up or down so that it rotates about its point of support, it twists the wire so that successive rods experience a twist in consecutive order.

The twist also generates a restoring torque which tends to bring the rods back to their original position. The result is that an angular pulse applied to one rod travels slowly down the wire, producing large and easily visible angular displacements. If one rod is moved in simple angular harmonic motion, a continuous running wave is sent down the wire. Interference between the outgoing and reflected waves produces standing waves.

Concepts

The nomenclature associated with waves – frequency, period, amplitude, wavelength etc. – is presented. Standing waves are produced by the superposition of two waves of the same frequency and amplitude going in opposite directions. Standing wave patterns are established only for the natural frequencies associated with the natural modes of oscillation of the system. Reflection with a change of phase which occurs at a fixed end is illustrated, as well as reflection with no change of phase which occurs at a free end. Damping is illustrated with the use of a hydraulic damping device. The pattern observed along the rods is a transverse wave with its characteristic nodes and antinodes. The concepts of torsion and restoring torque are shown in connection with the twist experienced by the rod.

SUPERPOSITION OF PULSES
B1590

Film Summary

A transverse pulse in the form of a crest travels from left to right on a straight line representing a stretched spring. Observation of a chosen point on the spring reveals that it moves only at right angles to the direction of pulse propagation when the pulse passes by it. A similar observation is made for a trough moving from right to left.

A crest and a trough starting at opposite ends of the spring meet at the center and obey the principle of superposition as they cross each other. The motion is repeated, and this time it is stopped several times to observe how the displacements y_1 and y_2 combine to produce the curve whose ordinate is $y_1 + y_2$. At a certain instant during the crossing $y_1 + y_2$ is everywhere zero.

A similar sequence is shown with two crests coming from opposite directions. This time, at a certain instant $y_1 + y_2$ produces an amplitude equal to the sum of the amplitudes of the two pulses.

Superposition of pulses in two sine wave trains of unequal amplitudes is then shown, followed by superposition of triangular and square pulses. The film ends with two sine pulses of identical frequencies and amplitudes crossing and forming standing waves for a very brief instant.

Concepts

The principle of superposition applied to single pulses or to wave trains asserts that if one pulse or wave can produce the displacement y_1 at a certain point and another can produce the displacement y_2 at the same point at the same instant, the combined displacement at that point is simply $y_1 + y_2$, where $y_1 + y_2$ are algebraic quantities that may be positive, negative, or zero. When two crests moving in opposite directions meet, a new crest is created momentarily whose amplitude is equal to the sum of the individual crest amplitudes. When a crest and a trough are combined, this sum is zero for an instant for many particles near the center of the spring. The spring, in other words, is straight where the two pulses meet and cancel each other.

The term interference is often given to the addition of displacements in obedience to the principle of superposition. This term is unfortunate because the pulses proceed after they cross, as if they had never met. In the usual sense of the word, they do not interfere. We see that the principle of superposition applies to pulses with special shapes and to short wave trains as well. Although the film does not illustrate it, the principle also applies to two and three dimensional media.

This ability of waves to cross in the same medium without permanently damaging one another is one of their most remarkable properties. The ripples formed by a pebble dropped into a still pond pursue their own circular densities despite the presence of ripples formed by other pebbles dropped nearby.

SUPERPOSITION OF PULSES IN A SPRING
81293

Film Summary

Crests are produced by hand simultaneously at both ends of a long spiral spring. They approach and pass each other, first at normal speed and then in slow motion. Throughout the interval of time during which they are crossing each other, the total displacement of a point on the spring rises to a maximum height which exceeds their maximum individual displacements. After the crests cross, their motion has not been changed by their encounter.

Three identical spiral springs are supported so that a single crest moves from left to right in one, a single crest moves from right to left in the other, and two crests move from opposite ends in the third. Pulses are started in all three spiral springs simultaneously. It is seen that the displacement at a point on the spring carrying two pulses is simply the sum of the displacements of the pulses considered separately. After the pulses cross going in opposite directions, they remain unchanged in shape and speed. This is dramatized by comparing what happens in the spring with two pulses in it to what happens to the single pulses in the other springs.

Similar experiments are performed using the three spiral springs by generating a crest at one end of one, a trough at the opposite end of another, and a crest and a trough simultaneously at opposite ends of the third. This time the displacements add up to zero momentarily at the center where the pulses meet, but later the pulses once again proceed with their motion unchanged.

Analogous experiments are shown for longitudinal pulses in which condensations and rarefactions replace crests and troughs.

Concepts

Applied to pulses, the principle of superposition states that if one pulse alone can produce the displacement y_1 at a certain point and another can produce the displacement y_2 at the same point at the same instant, the combined result is simply y_1 plus y_2, where y_1 and y_2 are algebraic quantities that may be positive, negative, or zero. The meaning of this principle is most clearly illustrated by the experiments with the three spiral springs in which pulses are produced simultaneously. When two crests meet, a new crest is created momentarily whose amplitude is equal to the sum of the individual crest amplitudes. This is especially clear in the case of transverse pulses. For the case of the combination of a crest and a trough the sum is briefly zero for many particles near the center of the spring, and there is no displacement there. The spring, in other words, is inert where the two pulses meet and cancel each other.

The term interference is given to the addition of displacements in obedience to the principle of superposition. This term is unfortunate because the pulses proceed after they cross as if they had never met; in the usual sense of the word, they did not interfer. Although we have illustrated the principle of superposition with pulses going in opposite directions in a one-dimensional medium, it also applies to pulses and waves moving in the same direction in a one-dimensional media as well. This ability of waves to cross in the same medium without permanently damaging one another is one of their most remarkable properties. The ripples formed by a pebble dropped on a still pond pursue their own circular destiny despite the presence of ripples formed by another pebble dropped simultaneously nearby.

REFLECTION OF WAVES IN A SPRING
** FREE END AND FIXED END **
81295

Film Summary

Reflections of transverse pulses and waves at a free end and at a fixed end of a long spiral spring are observed at normal speed and in slow motion. Each experiment begins with a reflection at a free end and is followed by a repetition of the experiment with a fixed end.

The incident and reflected pulses from free and fixed ends are shown for a crest, a trough, and a combination of a crest followed by a trough.

Concepts

For transverse pulses a crest is reflected as a crest and a trough as a trough when the reflecting end is free. Similarly, a crest is reflected as a trough and a trough as a crest when the reflecting end is fixed. This implies that the phase change on reflection is zero at a free end and 180 degrees at a fixed end.

SUPPLEMENT TO CHAPTER
INFORMATION ON WAVE DYNAMICS

In class discussion of Chapter 15, the question of why a wave moves as it does should be avoided insofar as possible. At this stage, students do not have the necessary preparation in mechanics to talk about even the simplest cases. However, the following discussion may be helpful as background information for the teacher.

As the wave shown on the rope in Figure 1 progresses to the right it passes the point P.

The piece of rope at P will rise and then fall. When it falls back to its original position it suddenly stops. Why doesn't it overshoot and go below its original position?

There are two possible answers to this question. One is that no point on a real rope or tube which is transmitting a wave stops suddenly. All real waves have rounded corners. The particles of the tube are only gradually accelerated and brought to rest. This is only a partially satisfactory answer since the more flexible the spring or tube used, the more nearly the "corners" of a wave can be sharp. However, discussion in class of this point can be avoided by using as examples smooth waves without sharp corners.

The second answer is found through considering the mechanics of a wave as it passes some point P. In Figure 2, consider the small bit of rope, Δx long, about the point P. We assume that the tension in the rope is T (newtons). That means that the rope is pulling the point P with a force T both to the right and to the left, as shown in the inset of Figure 2. The net force on the bit of rope at P is zero. By Galileo's principle of inertia, the piece of rope must be standing still or moving with a uniform velocity. Since the wave has not yet arrived at P we know that it is standing still.

Next let us consider a later time when the pulse has progressed to the point shown in Figure 3. Here the rope at P is stretched somewhat more than in Figure 2 and hence has a tension T'. We will avoid for the moment how T' is related to T, the tension in the level part of the rope. Again we see in the inset that the piece of rope at P is pulled just as much one way as the other and again the point P must be at rest or in uniform motion.

Referring to Figure 4, we see the wave drawn at one time and dashed at a time t later. During this time the wave has moved a distance S and the point P has moved up a distance D. The velocity of the wave

Fig. 1

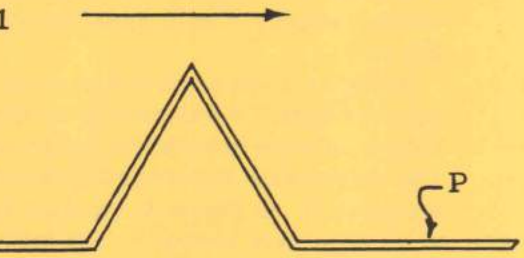


Fig. 2

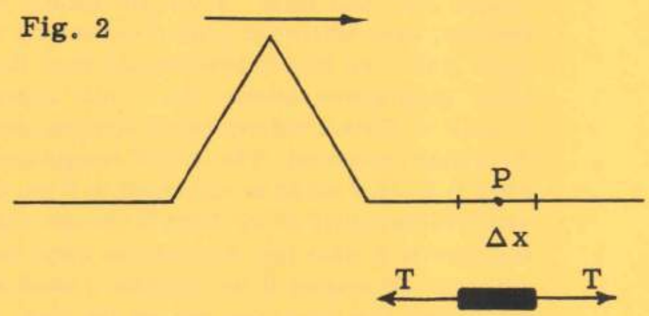


Fig. 3

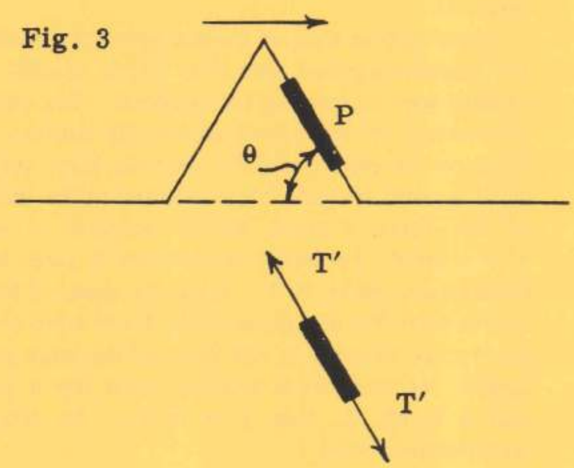
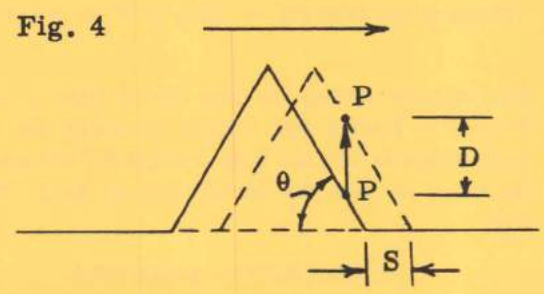


Fig. 4



is thus $v = S/t$ and the point P is moving up with a velocity $D/t = V$. We easily divide these two equations to get $V = v\dfrac{D}{S}$, and since $D/S = \tan\theta$, we see that $V = v\tan\theta$. Furthermore we can see that all points along the front slope of the wave are moving with the same velocity V. Similarly, if the pulse is symmetrical, all points on the back slope of the pulse are moving down with the velocity V. The point P in Figure 3 is thus moving up with a uniform velocity V as it must since the net force on it is zero.

In Figure 2, the point P was at rest. At the later time in Figure 3 it was moving up with a velocity V. Clearly, at some intermediate time it was accelerated. This acceleration occurred while the corner was passing point P. In Figure 5, the wave has just arrived at the segment of rope at P. The inset shows that the bit of rope is being pulled to the right with a force T. Now, however, the rope to the left does not just "cancel out" this force. If we are dealing with an idealized wave where the point P moves only up and down (this is an idealization because there is usually some longitudinal motion on a real rope), then $T'\cos\theta = T$ since the horizontal components of the force must cancel out. The vertical component of the force is $T'\sin\theta$ which is also equal to $T\tan\theta$. This vertical component of the force is the one that jerks the rope at P from rest into motion when the wave goes by. Of course, if we consider a small enough bit of rope this force does not act for long. It acts only long enough for the wave to progress the distance Δx.

When a force acts on some object for a short time, the impulse method (see Part III) is usually a convenient way of treating the problem. The change in momentum of the object equals the product of the force on the object and the time the force acts. The rope at point P starts from rest, and under the action of the force $T\tan\theta$, finally acquires a velocity $V = v\tan\theta$. Its initial momentum is zero; its final momentum, mass $\times$ V. Now the mass of the rope at P is zero, but the mass of the bit of rope of length Δx is $\mu\,\Delta x$ where μ is the mass of the rope per unit length. (If the whole uniform rope has a mass M and a length L, then $\mu = M/L$.) Its change in momentum is thus

$$\text{change in momentum} = \text{mass} \times V = \mu\,\Delta x v \tan\theta.$$

The impulse acting on this bit of rope is a force $T'\sin\theta = T\tan\theta$ (see Figure 5) acting for a time $\Delta x/v$ which is just the time it takes for the corner of the wave to pass the bit of rope Δx long. Finally, then

$$T\tan\theta\,\Delta x/v = \mu\,\Delta x v\tan\theta.$$

Fig. 5

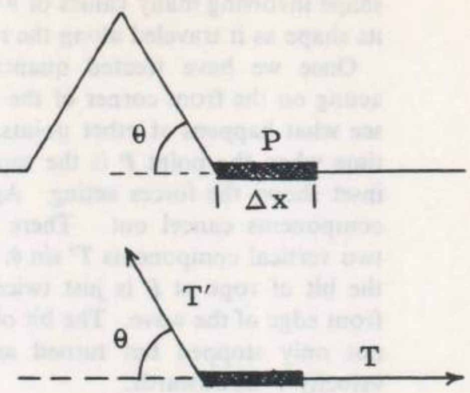


Fig. 6

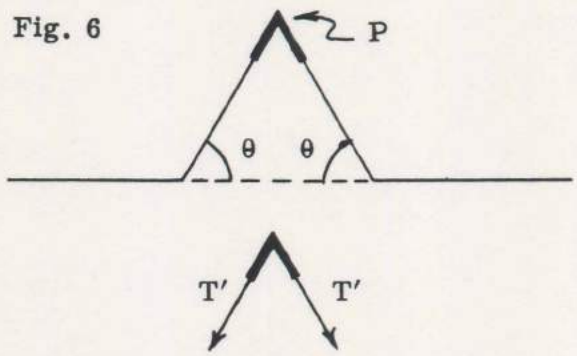
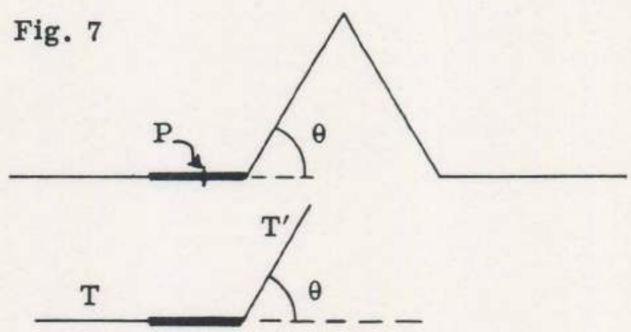


Fig. 7



Canceling, we have $T/v = \mu v$. Notice that Δx canceled out, which means that it didn't matter how long a little piece we considered. Since our choice of Δx was arbitrary, this must happen. Rearranging the last equation we find

$$v^2 = \frac{T}{\mu}; \qquad v = \sqrt{\frac{T}{\mu}}.$$

This shows that the velocity of a wave is greater when the tension is greater, and smaller when the mass per unit length is greater. The fact that the angle θ canceled out of the expression is important, for if it had not, waves of different shapes would travel with different velocities, and a wave with a complicated shape involving many values of θ would not maintain its shape as it traveled along the rope.

Once we have treated quantitatively the forces acting on the front corner of the wave, we can easily see what happens at other points. Figure 6 shows a time when the point P is the top of the wave. The inset shows the forces acting. Again, the horizontal components cancel out. There are now, however, two vertical components $T' \sin \theta$. The impulse given the bit of rope at P is just twice as great as at the front edge of the wave. The bit of rope P is therefore not only stopped but turned around and given a velocity V downwards.

Then as shown in Figure 7, the point P comes to the back corner where a force $T \sin \theta$ acts on it in such a direction as to stop the bit of rope at point P. The impulse is just the right amount to bring the bit of rope to a dead stop without overshooting.

We have considered the mechanics of the passage of a particularly simple type of wave. Net forces on the particles of the rope occur only at the corners. Here, since they act on small bits of rope they create violent accelerations. The accelerations last only for very short times and occur in such a way as to give rise to smooth wave motion. A wave pulse is, in general, curved smoothly. The forces which act on bits of rope are greatest where the curvature of the rope is greatest. A complete treatment of wave motion along a rope involves the solving of partial differential equations (see, for example, R. A. Becker, *Introduction to Theoretical Mechanics*, Chapter 15), and we will not consider it here.

A convenient medium for studying the property of waves in one dimension is the "slinky" spring. In this exercise it will be used to answer some basic questions concerning the motion of a single wave pulse.

A. TRANSVERSE WAVES IN A SPRING

Place the slinky on the floor and extend it so that it is under tension. About 3 meters stretch should be sufficient. Be careful not to over-extend the slinky, since this causes permanent distortion.

1. Generate pulses by giving the slinky a flick at right angles to the length of the slinky. Can you make different pulse shapes? Describe how you make different pulse shapes.

2. How fast do the pulses travel? Estimate the speed of the pulse. To do so, make rough estimates of appropriate quantities and calculate a value.

3. Can you change the pulse speed? What factors seem to affect this particular quantity?

4. Observe carefully what a specific point on a slinky does as a pulse goes by. Compare your observation with Figure 22-2, page 450 of your text.

5. What is simultaneously happening to particles of the slinky at the front and rear portions of the wave front at any instant of time. How does Figure 22-3 and Figure 22-4 relate to your observations?

6. Make a wave pulse having a shape as shown at the right. Observe its propagation and then make your own sketches, corresponding to Figure 22-2 and Figure 22-3 showing what particles of the slinky along the pulse shape are doing as the pulse moves first a small distance from left to right, and second, a small distance from right to left.

7. You have surely noticed that the wave shape changes as it moves along the slinky. What do you think is happening here? How would you expect the wave pulse to behave if the slinky were suspended so that it didn't touch the floor? What if it were suspended in water?

8. Make further observations of a single point or particle of the slinky as a pulse goes by from right to left. Sketch the up and down deflection of a particle as a function of time.

While observing the propagation of pulses on the slinky, you may have noticed that the wave does not vanish when it arrives at the far end. If you have noticed what happens, pat yourself on the back for being observant. We have deliberately not focused attention on this phenomenon. We will return for a detailed study at a later time.

If you were asked, could you explain, define, or contrast the following:

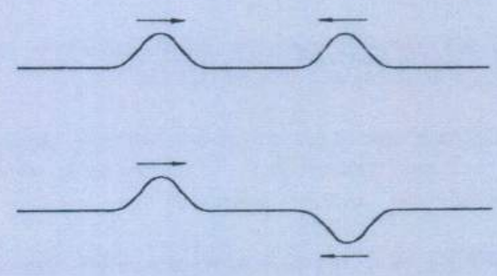
1. "medium" of propagation?
2. "transverse" wave?
3. propagation velocity vs particle velocity?
4. amplitude?

B. "COLLISION" OF WAVE PULSES: SUPERPOSITION

For this part of the experimentation, you and your partner will shake pulses at opposite ends of the slinky.

1. Make a study of what happens when two wave pulses sent from opposite ends encounter each other at the middle of the slinky. Try numerous combinations: pulses with same and opposite directions, different sizes, shapes, etc.

2. Sketch your own pictures of what you see happening, instant by instant when transverse pulses such as those shown at the right pass through each other. Does the pulses assume their original shape after having passed through each other? Compare your observations to Figures 22-5 and 22-6.



3. Figures 22-7 and 22-8 show the superposition of pulses of opposite deflection. How can one explain the cancellation of the two pulses, making the slinky straight at the instant when they overlap? Why does the slinky look fuzzy and not like a slinky at rest in the fifth frame? How does Figures 22-6 and 22-8 illustrate the resultant shape of the pulses as they pass through each other?

4. On a separate piece of paper apply the superposition principle to the nonsymmetrical pulses in Figure 22-9. Work out each stage without copying. How do you account for the fact that only one point on the slinky, the center point marked by the dashed line P, is never deflected and is thus always at rest?

C. REFLECTION AND TRANSMISSION

1. Have your partner hold one end of the slinky firmly without allowing the end to move when a pulse arrives. Send a transverse pulse down the slinky and observe the reflection carefully. How does the orientation of the reflected pulse compare to the orientation of the incident pulse? Examine Figure 22-10 carefully. Do your observations agree with the effects shown? Does the reflected shape make sense in terms of your present knowledge of wave behavior?

2. Let us now make one end of the slinky as free as possible by connecting 3 or 4 meters of thread to one end which is needed to keep the slinky stretched. Study the reflection of a transverse pulse from the free end. How does the reflected pulse compare with that observed from the fixed end? Does your observations confirm that which is shown in Figure 22-13?

3. Secure a heavy, smaller diameter spring securely to the slinky. Place the slinky-spring combination under tension by stretching the combination 4 or 5 meters. What happens to transverse pulses initiated on the slinky as they arrive at the boundary with the spring? What happens to transverse pulses initiated on the spring as they arrive at the boundary with the slinky?

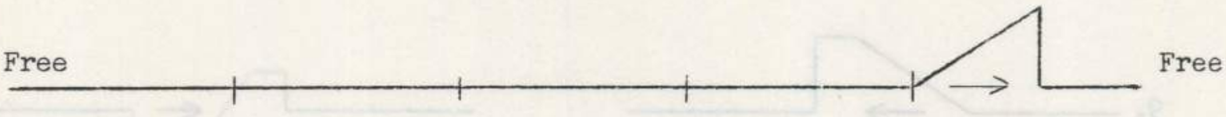
   Do your observations confirm the effects exhibited in Figures 22-11 and 22-12? Does the reflected upside down pulse in Figure 22-11 and the reflected right side up pulse in Figure 22-12 make sense in terms of what you observed when a pulse was reflected from a fixed and free end as observed in parts 1 and 2 above?

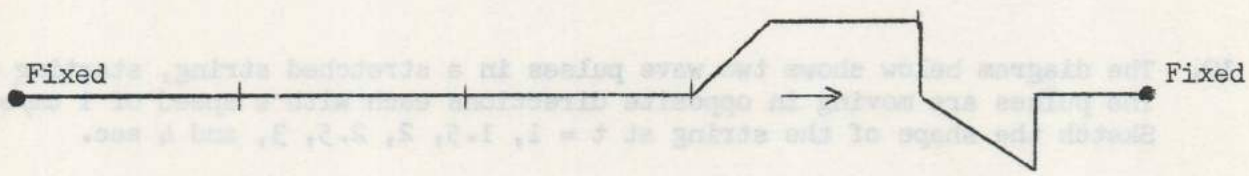
SCAMP

MICKEY MOUSE

Chapter 22 Construction Worksheet

The drawings below represent coil springs having end points separated by 5 meters. Under these conditions, waves travel at the rate of 10.0 meters per second in the coil springs shown below. (Assume the speed remains the same in both the heavy and light coil.) Make a drawing to show the <u>shape</u>, <u>position</u>, and <u>direction</u> of travel of the wave or waves that will be moving along the coil spring (0.4 seconds) later than shown in each of the drawings below.

1. 

2. 

3. 

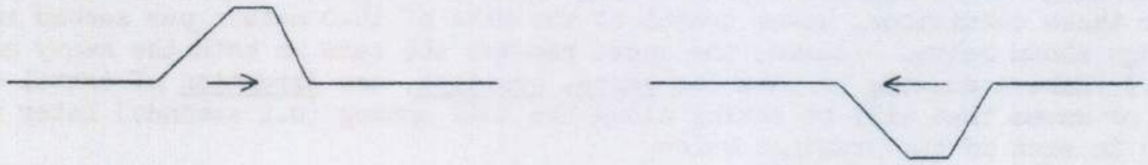
4. 

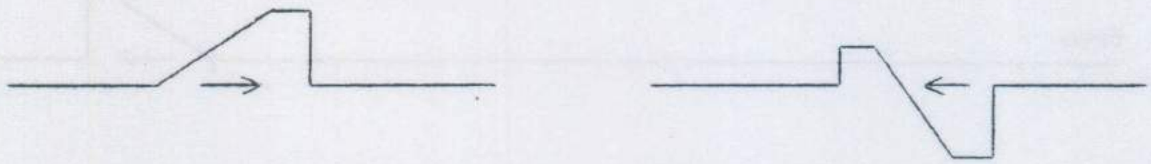
The following drawings represent coil springs with two waves approaching each other. Make a drawing (in the marked area) to show the shape of the combined wave resulting from the two waves as they are moving through each other. At this time, one of the waves should be right over the other.

5. 

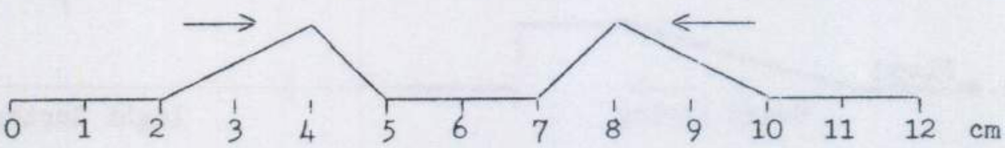
6. 

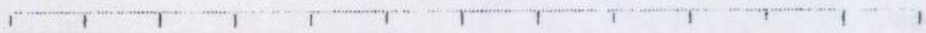
7. 

8. 

9. 

10. The diagram below shows two wave pulses in a stretched string, starting at t = 0. The pulses are moving in opposite directions each with a speed of 1 cm/sec. Sketch the shape of the string at t = 1, 1.5, 2, 2.5, 3, and 4 sec.

t = 0 

t = 1 

t = 1.5 

t = 2 

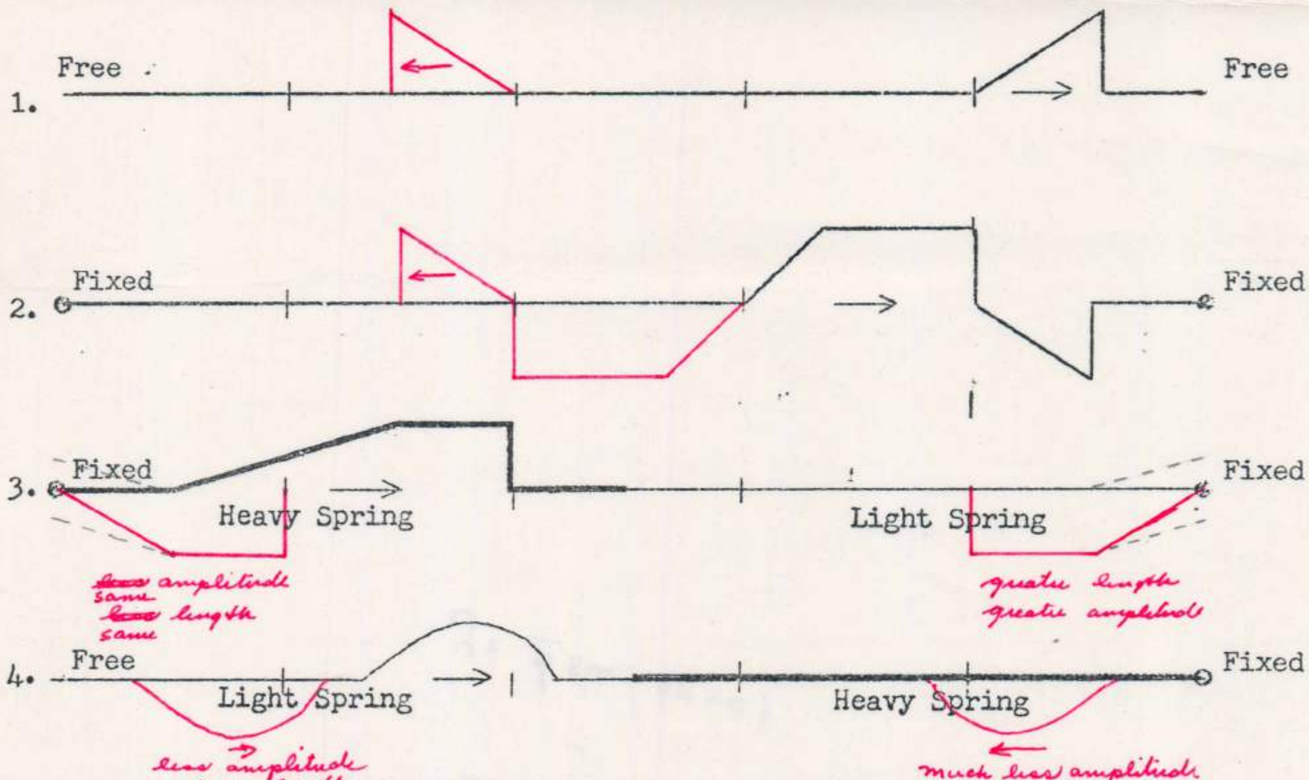
t = 2.5 

t = 3 

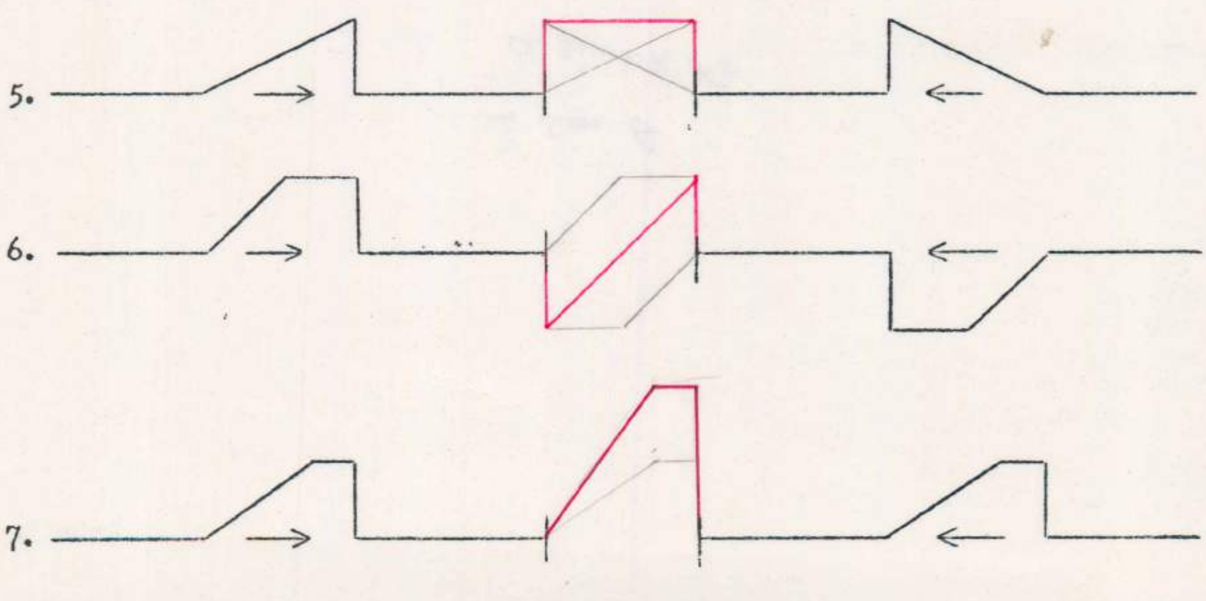
t = 4 

Chapter 5 Construction Worksheet

The drawings below represent coil springs having end points separated by 5 meters. Under these conditions, waves travel at the rate of 10.0 meters per second in the coil springs shown below. (Assume the speed remains the same in both the heavy and light coil.) Make a drawing to show the shape, position, and direction of travel of the wave or waves that will be moving along the coil spring (0.4 seconds) later than shown in each of the drawings below.

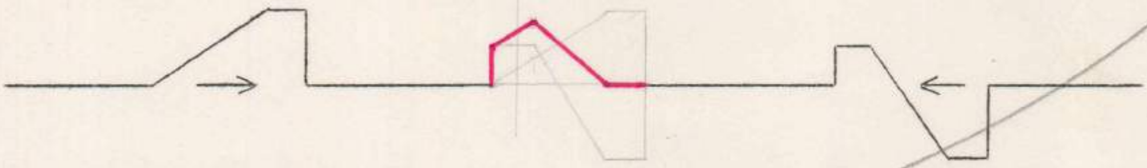


The following drawings represent coil springs with two waves approaching each other. Make a drawing (in the marked area) to show the shape of the combined wave resulting from the two waves as they are moving through each other. At this time, one of the waves should be right over the other.

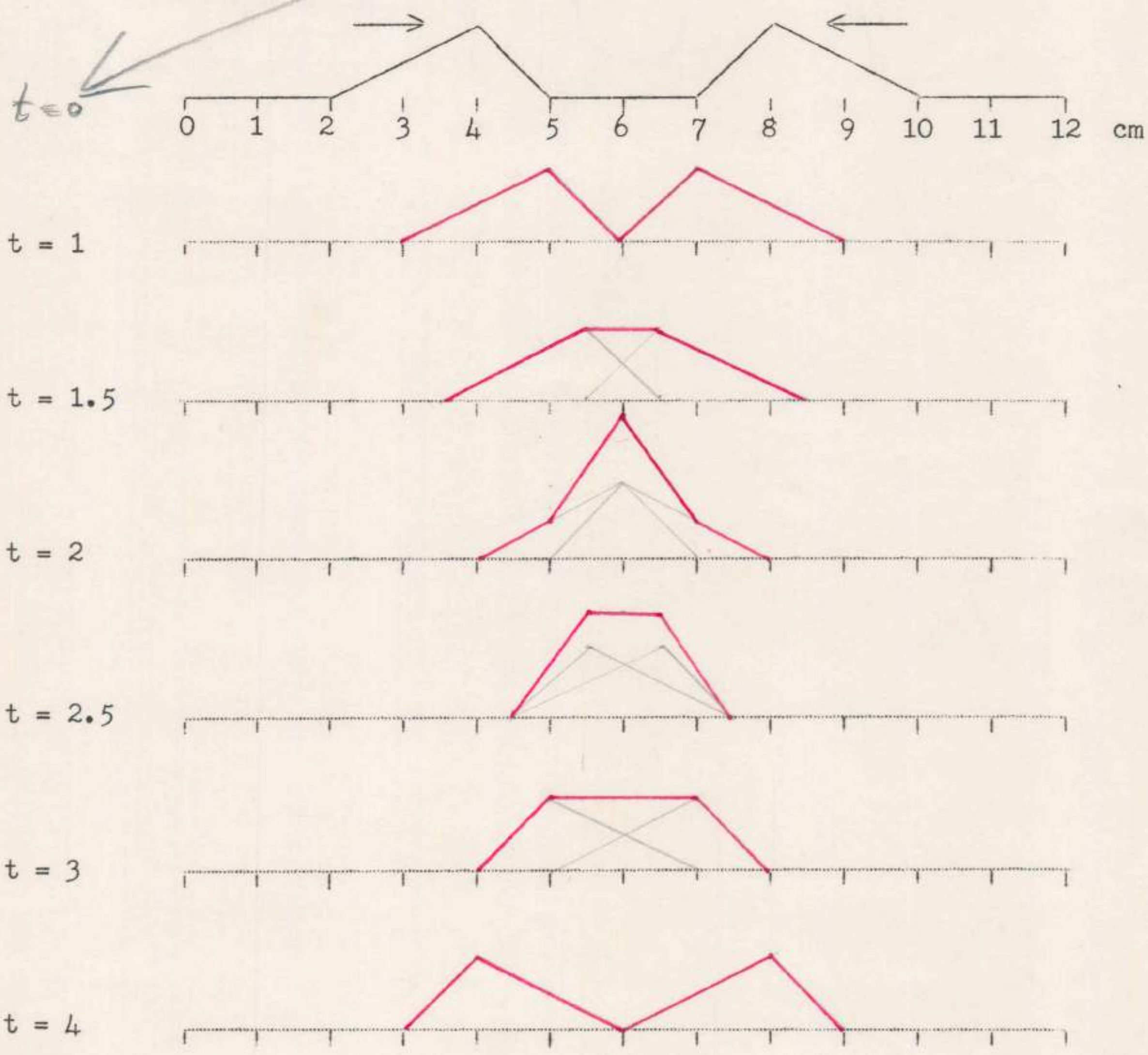


odd

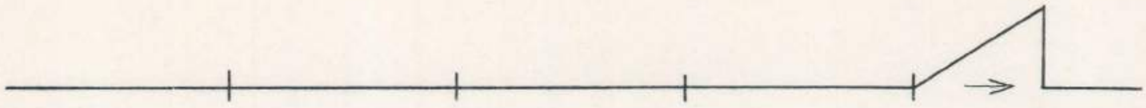
8. 

9. 

10. The diagram below shows two wave pulses in a stretched string, starting at t = 0. The pulses are moving in opposite directions each with a speed of 1 cm/sec. Sketch the shape of the string at t = 1, 1.5, 2, 2.5, 3, and 4 sec.



1.



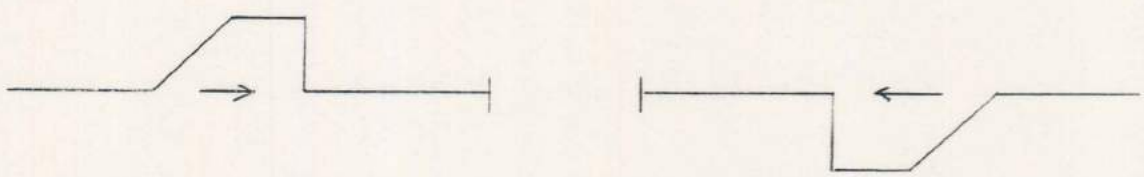
2.

3.

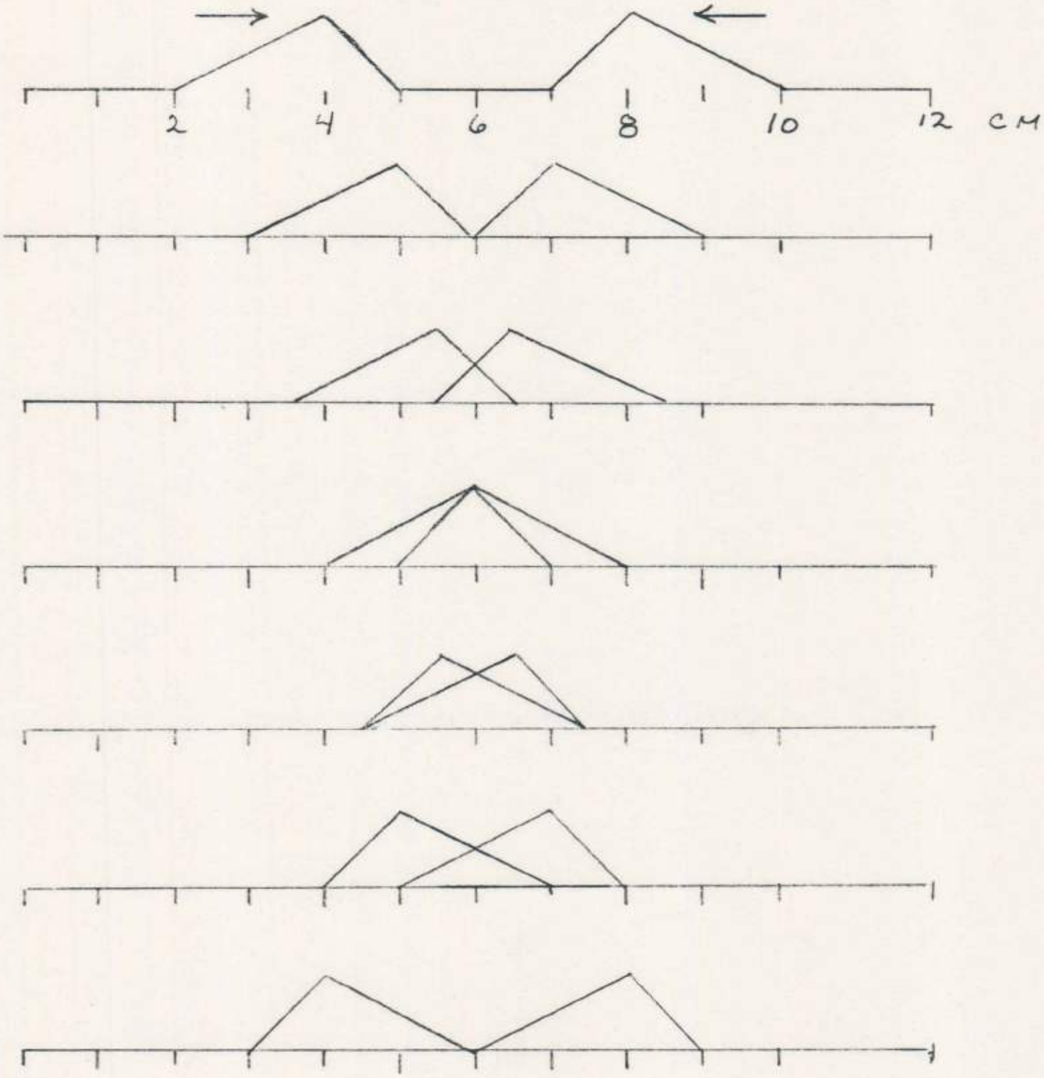
4.

5.

6

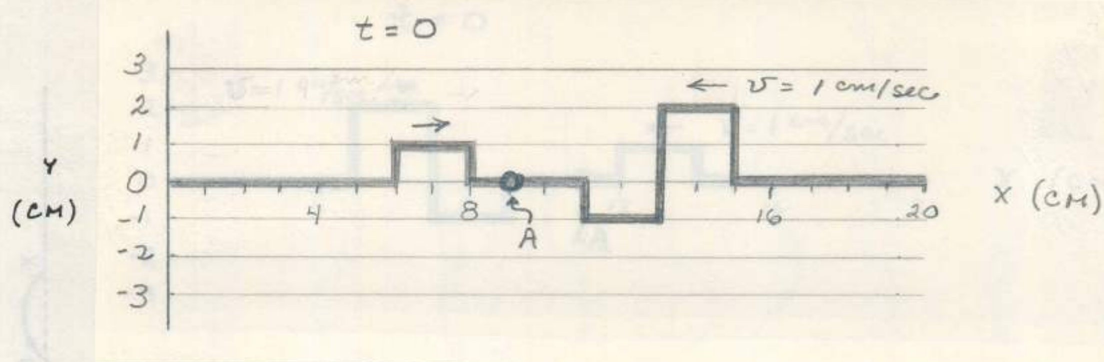


7.

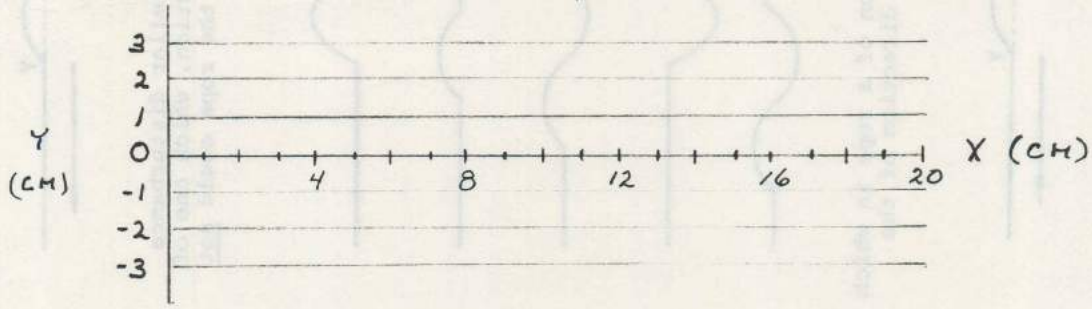


2
4
6
8
10
12 CM

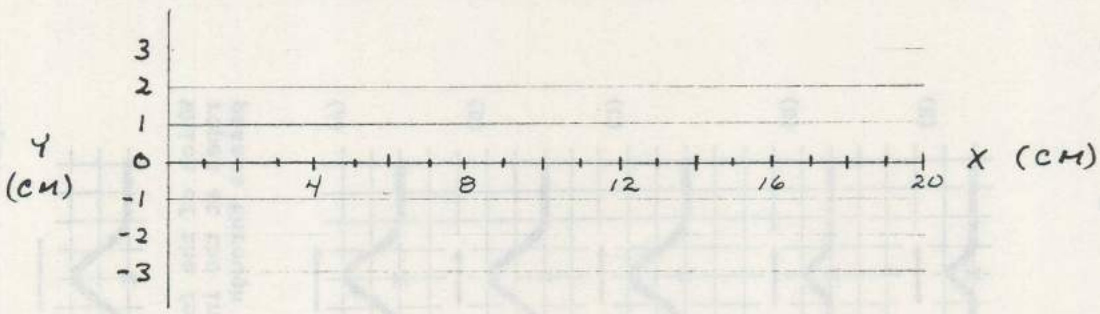
Principle of Superposition



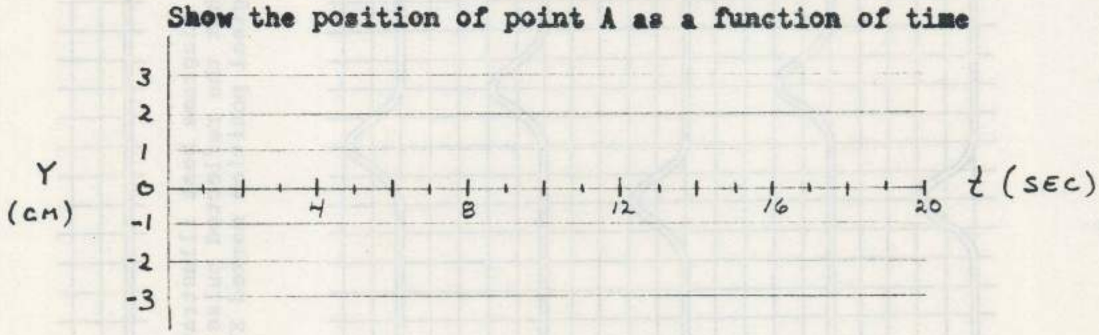
Show the shape of the slinky at t = 2 sec



Show the shape of the slinky at t = 3 sec



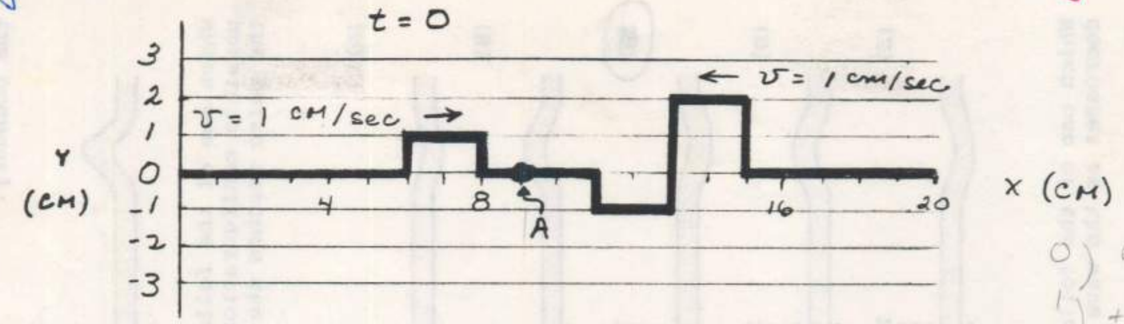
Show the position of point A as a function of time



Chapter 22 Test -4- Name

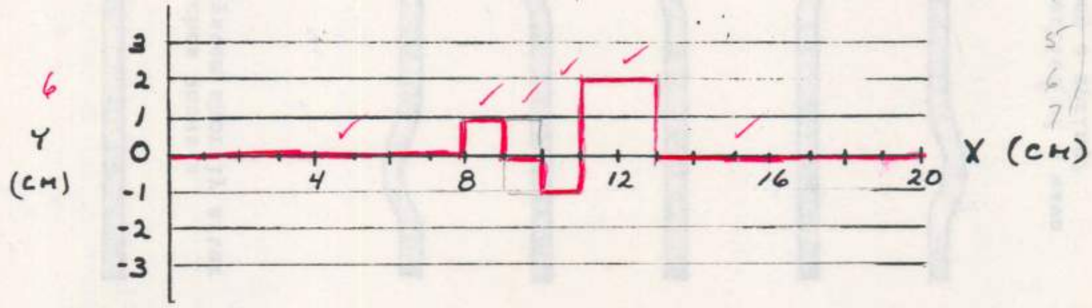
38

Principle of Superposition



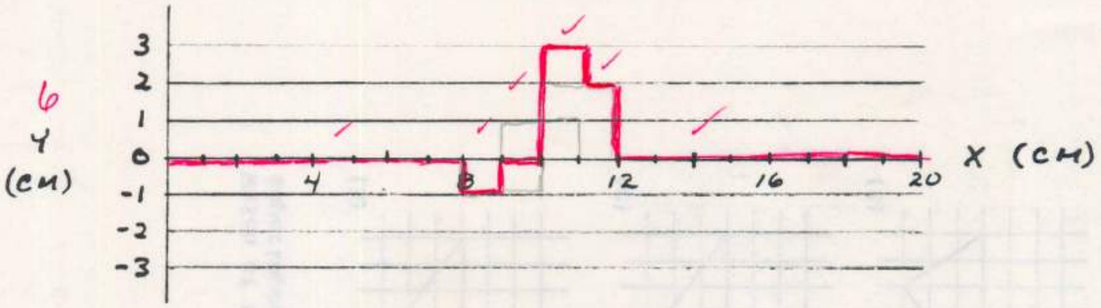
Show the shape of the slinky at t = 2 sec

6



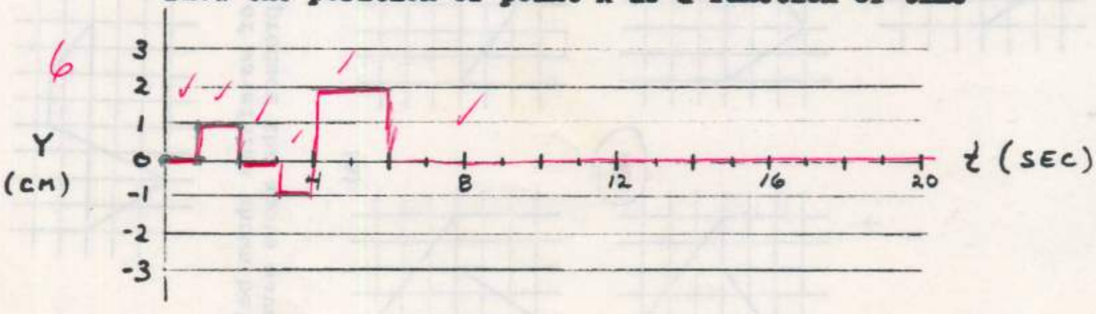
Show the shape of the slinky at t = 3 sec

6



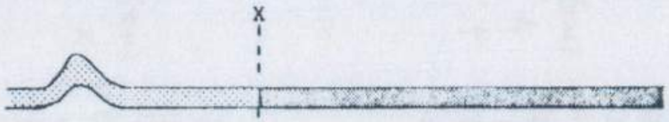
Show the position of point A as a function of time

6



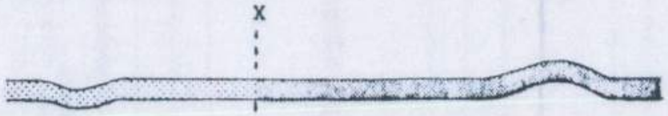
18

1 The line X represents the boundary between two dissimilar springs. A pulse is shown approaching the boundary.

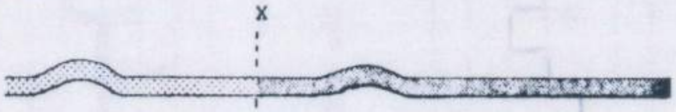


Which one of the following sketches shows a possible configuration of the system shortly after the pulse reaches the boundary?

(A)



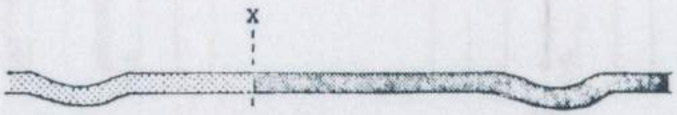
(B)



(C)

(D)

(E)



2 Which one of the following properties of a wave decreases as the wave moves along a spring?

(A) amplitude

(B) wavelength

(C) speed

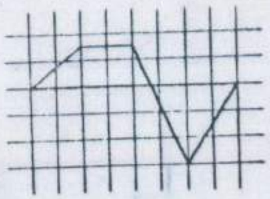
(D) frequency

(E) period

D A E A A

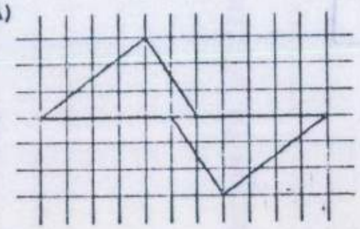
E E D C A

3 The waveform shown below was produced by a superimposed waveforms.

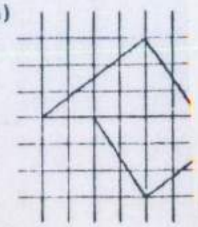


Which of the pairs of waveforms shown below superimposed could produce the above wavefo

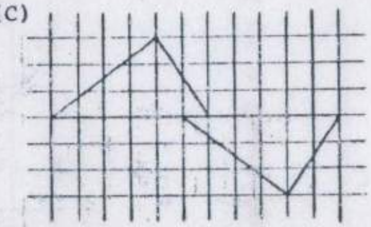
(A)



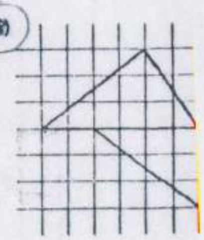
(B)



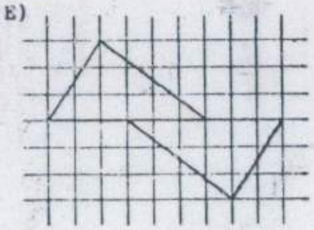
(C)



(D)



(E)



20

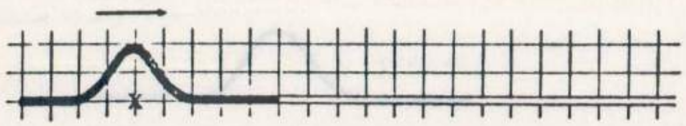
Key

1. C 2. A 3. D 4. E 5. _

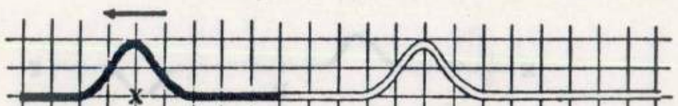
6. A 7. A 8. A 9. E 10. _

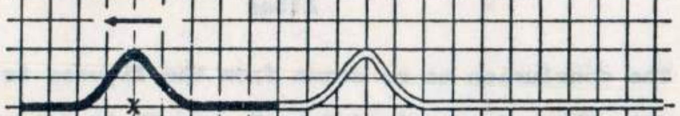
Alternate

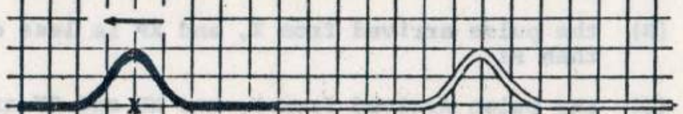
4 The diagram below shows a transverse pulse travelling along a heavy rope toward its junction with a lighter rope.

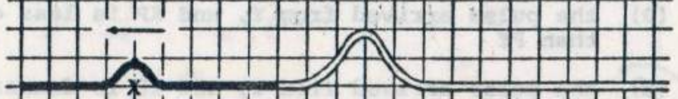


Which of the following diagrams best illustrates the ropes at the instant that the reflected pulse again passes through its original position marked X?

(A)


(B)


(C)


(D)


(E)


5 The diagram below shows a portion of a rope in which a disturbance XY travels in the direction of the arrow.

If the disturbance XY meets a similar disturbance travelling in the opposite direction, which one of the following configurations of the rope could not appear?

(A)


(B)


(C)


(D)

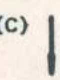

(E)


6 The diagram below shows a portion of a rope in which a disturbance XY travels in the direction of the arrow.

The instantaneous velocity of a particle of the rope at point P is best represented by which one of the following vectors?

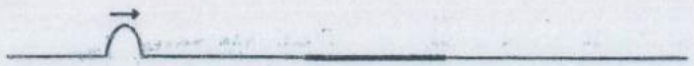
(A)

(B)

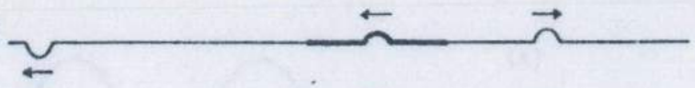
(C)

(D)

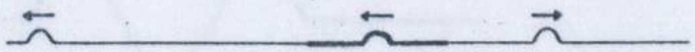
(E)

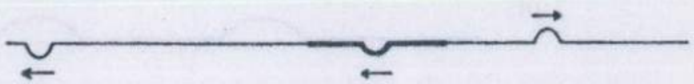

7 The diagram below shows a pulse travelling to the right along a light rope attached to a heavy rope which is in turn attached to a light rope. The first and third ropes are identical.

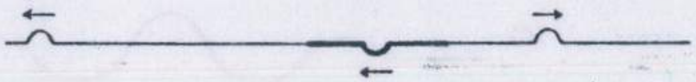


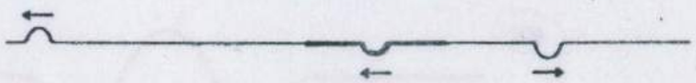
A short time later the ropes will appear most like

(A) 

(B) 

(C) 

(D) 

(E) 

8 The wavelength of a transverse wave train is 20 cm and its amplitude is 4 cm. At a point P the displacement is -4 cm. At the same instant, at point Q, 25 cm away in the direction of propagation of the wave, the displacement is

(A) 0 cm

(B) 2 cm

(C) -2 cm

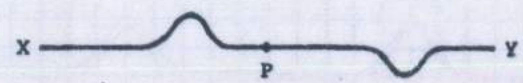
(D) 4 cm

(E) -4 cm

9 Two ropes XP and PY are joined together with a knot at P. An upward pulse such as that shown in the first figure (Pulse) is passed along the string to the knot, where part is transmitted and part is reflected.

Pulse

Shortly after this, the two pulses leaving the knot appear as shown in the second figure (After).



After

The conclusion to be drawn from the figures is that

(A) the pulse arrived from X, and XP is denser than PY

(B) the pulse arrived from X, and XP is less dense than PY

(C) the pulse arrived from Y, and XP and PY are equally dense

(D) the pulse arrived from Y, and XP is less dense than PY

(E) the pulse arrived from Y, and XP is denser than PY

10 When a transverse wave travelling on a string reaches the junction with a lighter string, the wave is

(A) totally reflected at the junction

(B) partially transmitted with a change in phase

(C) transmitted forming a standing wave pattern in the lighter string

(D) reflected so as to form a node at the junction

(E) partially reflected without a change in phase

Unit 9: INTRODUCTION TO WAVES: ANOTHER MODEL

Previous units have given us some good ideas with which we can begin to describe the behavior of reflecting and refracting light. However, a simple particle model of light was not adequate to correctly describe how light behaves in all aspects. Again we must ask, what is the nature of light if it is not like a particle? A good next guess, for reasons which will become apparent in the reading, is that light behaves like a wave. In this unit, we will take a look at how the simple wave behavior of a pulse on a spring can correctly predict many features of light. Then, in later units, we will refine the model and see that the wave model predicts some properties of light that most of us never see in ordinary circumstances.

Objectives

1. For a spring connected either rigidly to a wall or to another spring, be able to determine the following when a specific height pulse is created on the spring:

   a) the height of the reflected pulse (and whether it is upright or inverted)

   b) the height of the transmitted pulse (and whether it is upright or inverted)

   c) if connected to a second spring, whether the pulse velocity is greater or less than on the first spring.

2. Be able to describe in a brief paragraph whether and why the simple one-dimensional wave model correctly predicts the behavior of light as it relates to (a) superposition of beams, and (b) the partial reflection and refraction of a light ray at the interface between two different substances.

Suggested Procedure

1. Read Chapter 6 of the text.

2. Read through the problem examples and then complete the guided problems.

3. Do the following exercises: 1, 3, 4, 7, 8, 10, 12, 15, 16, 17.

Do the lab exercise(s) suggested by your instructor.

4. You may have at home a "slinky" or a long rope (like a clothesline). Both of these objects are excellent wave carriers, and if they are available to you, you might try some investigating of wave pulses on your own.

5. Take the unit test when you feel that you are ready.

Guided Problems

1. Describe in a brief paragraph whether the behavior of pulses traveling on a spring made of a light and a heavy section simulates the behavior of light as it passes from one substance into another.

   Guided Solution: a) When a pulse is sent down one of the springs, will there be a pulse transmitted onto the other section of spring?

   b) Will there be a pulse reflected from the junction of the two sections of the spring?

   c) When a light beam is incident onto a surface of another transparent medium, do we see both a reflected and a refracted beam?

   d) On the basis of (a), (b) and (c), does the behavior of a pulse interacting with the junction of a two-section spring correctly simulate the behavior of the light as it strikes the surface of a transparent substance?

2. A spring is made up of two sections of equal length. The second section is more massive than the first. A single pulse is sent along the first section of spring.

   i) After the initial pulse encounters the second section, there will be a pulse which continues onto the second more massive section of spring. Will this pulse be higher or lower than the original pulse?

   ii) Will this pulse be moving faster or slower than the original pulse?

   iii) There will be a reflected pulse. Will it be inverted or upright compared to the incident pulse?

   Guided Solution: a) With a pulse traveling along a two-section spring, we know that there will be both a transmitted and a ________________ pulse.

   b) Each of the pulses described in (a) is always ____________ ____________ in height than the original pulse. From this, you can answer part (i).

   c) A pulse travels ______________ on a massive spring than on a light spring. From this result you can answer part (ii).

   d) What is the general rule for determining whether a reflected pulse is right side up or upside down?

(cont'd)

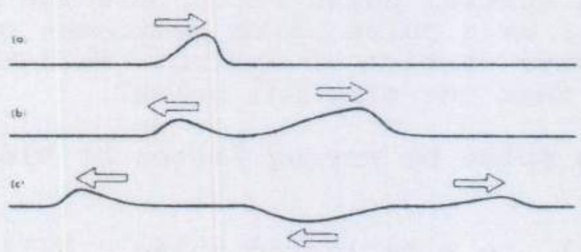
e) Apply this rule to answer part (iii).

Problem Examples

1. Describe in a brief paragraph whether this superposition of pulses on a spring correctly predicts the behavior of two intersecting beams of light.

   Solution: As can be seen from the illustrations in the text, the shapes of individual pulses after they have "collided" on a spring are the same as their original shapes. (Although during the "collision", the shape of the combined pulse often gets quite complex.) We observe in everyday life that two light beams crossing each other do not appear to cause any change in either beam. Therefore, for the superposition (or collision) of light beams, our wave model seems to describe the non-interaction of light beams with each other very well.

2. This is problem number 19 of chapter 6. The figure shows a pulse moving along a rope which has sections of different densities. Diagram (b) and (c) show the same rope at equal intervals of time later. Where are the junctions of the different densities of rope and what are the relative densities of the various sections of rope?



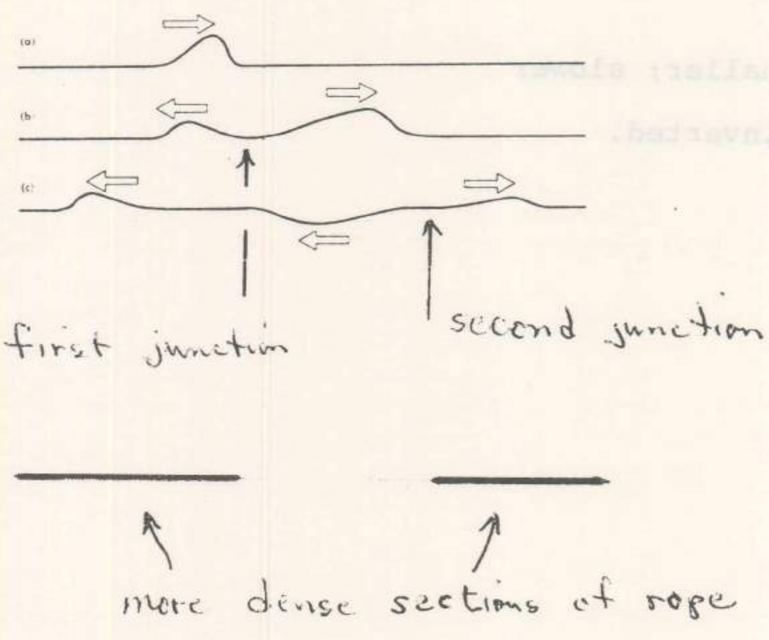
   Solution: First of all, we recall the general rule for determining whether a reflected pulse is right side up or upside down. If the pulse is reflected at a junction with a lighter spring, the reflected pulse is right side up, and if it occurs at a junction with a heavier spring, then the reflected pulse is upside down. (To make this easier to remember, perhaps you might recall that in the "extreme" case where the end of the spring is rigidly fixed -- that is, connected to a very, very massive body - the reflection is always upside down.

   Now, by comparing diagrams (a) and (b), we see that the transmitted pulse in (b) is stretched out, which means that its velocity is greater. If the velocity is greater at the right side, we know that the density of the rope must be less at

(cont'd)

the right end than at the left end. In (b) we know that the wave on the left is moving toward the left. Therefore, in (b), the two pulses going in opposite directions tells us that the first junction of the ropes of different density must be somewhere between the pulses to the right of where the lone pulse is in diagram (a).

Let's look at diagram (c). The reflected pulse on the left has moved farther toward the left without changing shape, so that pulse could not have encountered a change in rope density. But something has clearly happened on the right. Now there are two pulses where before (in b) there was only the long pulse moving toward the right. The height of each of these two new pulses is less than that of the pulse on the right side of (b). We are led to deduce that the pulse on the right of (b) has divided into the two new pulses. Since this new pulse moving to the left is inverted, the junction in the rope must be such that the rope becomes more dense as we move to the right. This assumption is confirmed by the narrower shape of the far right pulse which indicates that it is moving more slowly. (A more dense rope will cause the pulse to travel more slowly and thus make its shape appear more narrow.)



This second change in density must be between the two pulses on the right of diagram (c) and in front of the right hand pulse in diagram (b).

To sum up, the "junctions" (or changes in density) in the rope are as shown above. Starting from the left, the rope is dense, then less dense and then more dense again (see illustration above).