8.3 Interference of Waves

SECTION OUTCOMES

- Explain and illustrate the principle of interference of waves.
- Communicate and graphically illustrate the principle of superposition.
- Analyze, measure, and interpret the components of standing waves.

KEY TERMS

- resultant wave
- component wave
- constructive interference
- destructive interference
- node
- antinode
- standing wave
- fundamental frequency
- fundamental mode
- overtone

When material objects such as billiard balls collide, they bounce off each other. One usually gains energy, while the other loses energy. In any case, they move off in different directions. In some cases, when an object has a large amount of energy and collides with another, the shape of the object undergoes a drastic change. It might break apart into many pieces or it might collapse or be crushed into an unrecognizable form. How do waves react when they meet?

The students in Figure 8.13 are sending wave pulses toward each other along the same spring. What will happen when the wave pulses meet? Will they collide and bounce off each other? Will the waves become distorted and unrecognizable? Will they simply pass through each other unchanged? Complete the following Quick Lab to find out for yourself.

Figure 8.13 How do collisions between wave pulses compare to collisions between material objects?

QUICK LAB

Do Waves Pass Through or Bounce Off Each Other?

TARGET SKILLS

- **Predicting**
- **Analyzing and interpreting**

Predict what will happen when two wave pulses meet. Give the reasoning behind your predictions. With a partner, stretch a large spring out along the floor, to a length of about 8 m. Start wave pulses from each end at the same time and observe what happens. Test all of the following combinations.

- pulses of the same size on the same side of the spring
- pulses of different sizes on the same side of the spring
- pulses on the opposite sides of the spring

Discuss with your partner what you perceive to be happening. If you do not agree, design more experiments until you feel that you have a clear understanding of what happens when wave pulses meet.

Analyze and Conclude

1. Did your final conclusion agree with your prediction? Explain any contradictions.
2. Describe your final conclusion about whether waves bounce off or pass through each other.
3. How did the design of your experiments help you to draw a firm conclusion?

Superposition of Waves

You no doubt concluded from the Quick Lab that waves *do* pass through each other. During the time that the two waves overlap, they interact in a manner that temporarily produces a different-shaped wave. This **resultant wave** is quite unlike either of the two **component waves**. Each component wave affects the medium *independently*. Consequently, at any one time, the displacement of each point in the medium is the *sum* of the displacements of each component wave. Note that the displacements of the component waves can be either positive (+) or negative (–). These signs must be included when adding them. If one wave would have moved a particular point in the medium up three centimetres (+3 cm), and a second wave would have moved that point down six centimetres (–6 cm), then the resultant displacement would be three centimetres down (+3 cm + (–6 cm) = –3 cm). This behaviour of waves is known as the “principle of superposition.”

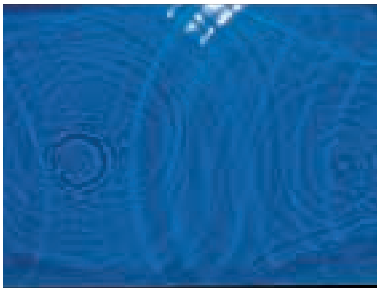

Figure 8.14 As these water waves move through each other, you can readily see the details of each individual wave.

When two waves displace the medium in the same direction, either up or down, the resultant displacement is larger than the displacement produced by either component wave alone. This interaction is called **constructive interference** (see Figure 8.15). As the wave pulses pass through each other and the peaks of each wave overlap, one point (A) in the medium will experience the maximum displacement.

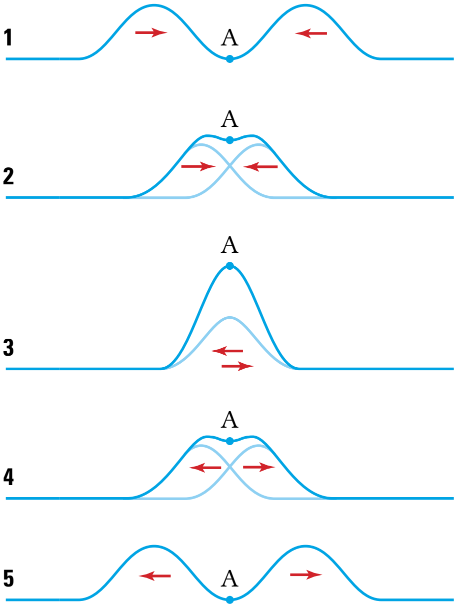

Figure 8.15 Constructive interference results in a wave pulse that is larger than either individual pulse.

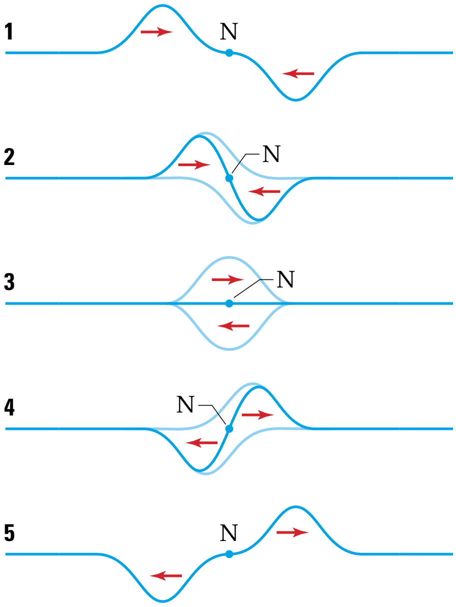

Figure 8.16 Destructive interference results in a pulse that is smaller than the larger of the component waves. When the component pulses are identical in size but one is inverted, there is one moment when no pulse can be seen.

When two waves displace the medium in opposite directions, the resultant displacement is less than one, and sometimes both, of the component waves. This interaction is called **destructive interference**, and is illustrated in Figure 8.16 on the previous page. If the two pulses are identical in size, the point where they first meet (N) will not move at all as the waves interfere.

Standing Waves

When periodic waves with the same shape, amplitude, and wavelength travel in opposite directions in a linear medium such as a rope or spring, they produce a distinct pattern in the medium that appears to be standing still. At intervals that are a half wavelength apart, the waves destructively interfere and create points, called **nodes**, that never move. Between each node, a point in the medium, called an **antinode**, vibrates maximally. Because the nodes do not move, the sense of movement of the two-component wave is lost and the resultant wave is called a **standing wave**.

Figure 8.17 illustrates how using the principle of superposition yields the pattern of fixed nodes, spaced half a wavelength apart, and points of maximum disturbance, or antinodes, also spaced half a wavelength apart. The antinodes are located at the midpoints between adjacent nodes. As you can see in part (A) of Figure 8.17, when the two identical component waves line up with troughs opposite crests, there is complete destructive interference and, momentarily, the medium is undisturbed.

A quarter of a period later, the yellow wave will have moved a quarter of a wavelength to the right and the blue wave will have moved a quarter of a wavelength to the left. Part (B) of Figure 8.17 shows how the two component waves are superimposed, producing constructive interference. This interference produces a resultant wave with an amplitude that is the sum of the component waves.

A quarter of a period after the situation depicted in part (B), the waves will again be lined up in opposition, so as to produce destructive interference in part (C). A quarter of a period later, the component waves will again be superimposed so as to produce constructive interference, as illustrated in part (D). This sequence will repeat over each period.

Part (E) of the figure represents the image you would see over a period of time. At the nodes, the medium does not move at all. In between the nodes, the standing wave appears as a blur, because the medium is moving up and down constantly. The resulting movement is characterized by a series of nodes spaced half a wavelength apart along the medium and a series of antinodes located at the midpoints between the nodes.

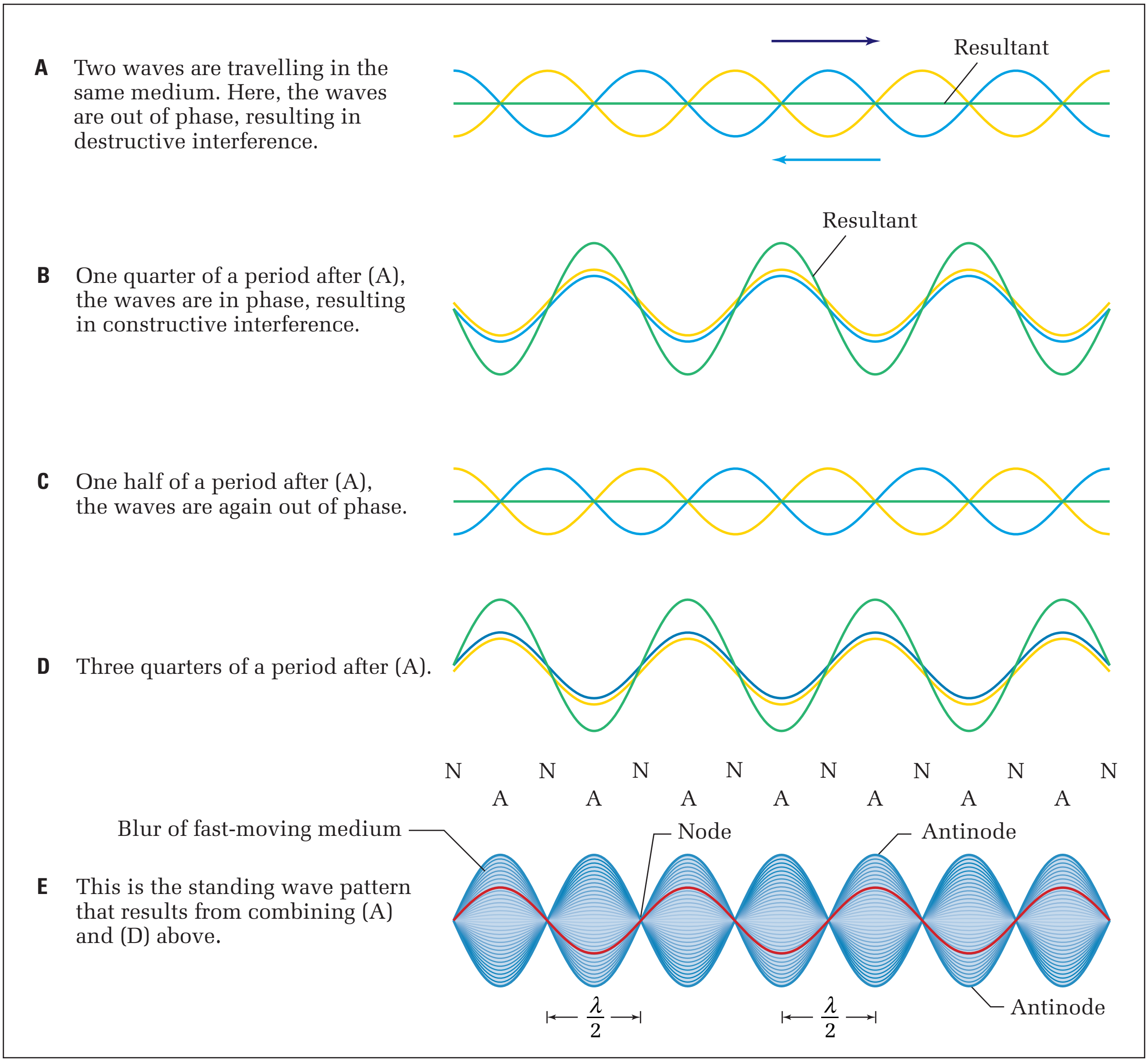

Figure 8.17 As identical travelling waves proceed one quarter of a wavelength in opposite directions, the resultant wave goes from complete destructive interference to maximal constructive interference. Part (E) shows how the wave appears over a period of time. The red wave shows the wave at one instant in time.

A standing wave can also be produced in a linear medium using only one vibrating source. The second wave is produced by the reflection of the first wave from the far end of the medium. Because the second wave is a reflection, it will have essentially the same frequency, wavelength, and amplitude as the first. Whether or not resonance and, consequently, a standing wave will occur depends on the match between the frequency of vibration and the length of the linear medium.

Figure 8.18 The position of a violinist's finger determines the effective length of the string and, therefore, determines which wavelengths will form a standing wave.

For example, consider a bow drawn across a violin string. The friction of the bow causes the string to vibrate at many different frequencies. Waves move in both directions away from the bow toward the fixed ends of the string. When they reach the ends, the waves reflect back. The propagated waves and the reflected waves interfere, sometimes constructively. Whether or not standing waves of a given frequency can form depends on the end points of the string where the string is fixed. Since the ends of the strings cannot move, standing waves can form only if nodes occur at the ends of the strings. When the string is vibrating at its resonance frequencies, it causes the body of the violin to vibrate and amplify the tone.

For every medium of a fixed length, there are many **natural frequencies** of vibration that produce resonance. Figure 8.19 shows a rope vibrating at three of its natural frequencies. The lowest natural frequency (corresponding to the longest wavelength) that will produce resonance on the rope is called the **fundamental frequency**. The standing wave pattern for a medium vibrating at its fundamental frequency displays the fewest number of nodes and antinodes and is called its **fundamental mode** of vibration. All natural frequencies higher than the fundamental frequency are called **overtones**. For example, the natural frequency that corresponds to a pattern with one node in the centre of the rope is called the "first overtone." The pattern continues with the addition of one node at a time. A rope or string may vibrate at several natural frequencies at the same time.

MISCONCEPTION

You can't get something for nothing!

Some people might think that constructive interference creates energy, or that destructive interference destroys energy. However, the law of conservation of energy still holds. Energy can neither be created nor destroyed. A standing wave simply redistributes the energy so that there is less energy near the nodes and more of it near the antinodes.

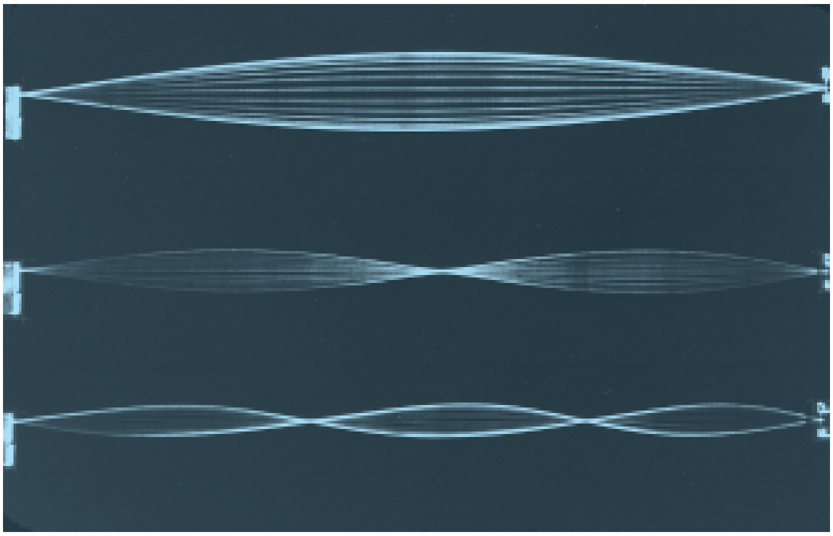

Figure 8.19 Resonance will occur in a vibrating rope for wavelengths that create nodes at the ends of the rope. There may be any number of nodes within the rope.

INVESTIGATION 8-B

Wave Speed in a Spring

TARGET SKILLS

- Performing and recording
- Analyzing and interpreting

If you know the speed of a wave, you can use it to determine the time it takes a wave to travel a given distance, or the distance a wave will travel in a given time. You can also use the speed to determine the wavelength of a wave when the frequency is known, or the frequency when the wavelength is known. The precision of any of these calculations depends on the precision with which the speed is known. Consequently, it is important to determine the speed as precisely and accurately as possible.

In this investigation, you will measure the speed of a wave using two different methods. Then, you will evaluate the methods and decide which is the more accurate. In order to make the best measurements, you will need at least three people in each group.

Problem

To determine the speed of a wave in a stretched spring as precisely as possible, and to evaluate the accuracy of the result.

Equipment

- long spring
- stopwatch
- metre stick or measuring tape

Procedure

Direct Measurement

1. Stretch the spring out between two partners. The third partner will carefully measure the length of the spring. Ensure that you maintain this length throughout the investigation.
2. Determine the optimum number of times that you can allow the pulse to reflect back and forth and still see the pulse clearly enough to make good time measurements. Send several test pulses down the spring to determine the optimum number of reflections to allow for one time measurement. (**Note:** You can increase the precision of your measurements by allowing the pulse to travel longer distances. However, as the pulse reflects back and forth, friction causes the amplitude to decrease. The amplitude eventually becomes so small that it is hard to follow and thus decreases the precision of your measurements.)
3. Devise a method for determining the exact distance that a pulse has travelled when you make a measurement.
4. Prepare a data table with the following headings: Distance, Time, Speed. Allow enough rows for at least five trials.
5. Carry out at least five trials for measuring the time and distance data for a moving pulse.
6. Calculate the speed of the pulse and determine the average speed for the five or more trials that you performed.

Indirect Measurement

7. To carry out an indirect measurement, you need to create standing waves in the spring. Practise the creation of standing waves by performing the following steps.
    - **(a)** Stretch the spring out to about 8 m.
    - **(b)** While one partner holds the end of the spring fixed, another should vibrate the opposite end back and forth.
    - **(c)** Start with a very low frequency and try to get the spring to vibrate in its fundamental mode. You should see only one node at the end held in place and one more node very close to the end that is being vibrated.
    - **(d)** Slowly increase the frequency of vibration until you can produce other standing wave patterns.
    - **(e)** Determine the values of all of the natural frequencies that you were able to find.

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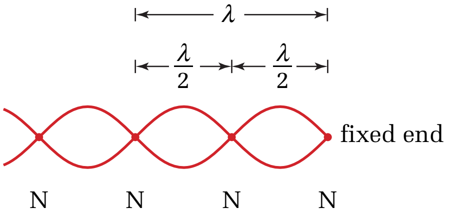
time for 20 vibrations Δt	$f = \frac{20}{\Delta t}$	λ = distance from fixed end to second node	$v = f\lambda$

8. Stretch the spring to exactly the same distance that you used when making the first set of measurements.

9. Prepare a data table like the one shown above. Allow for at least five trials.

10. One partner should hold one end of the spring firmly in place, while a second partner creates a standing wave by vibrating the other end of the spring. Find a frequency that creates at least two nodes in the spring.



11. Let the third partner determine the wavelength by measuring the distance from the stationary end to the second node. Record the value in the data table.

12. Determine the time for 20 vibrations. Record the value in the data table.

13. Repeat steps 10 through 12 for at least five trials.

14. Calculate the speed of the wave for each trial. Determine the average of the speeds for all trials.

Analyze and Conclude

1. Compare the precision of measurement for the two methods for determining the speed of a wave. (**Note:** The range of the speeds in individual trials for each method is an indicator of precision. A narrow range of values indicates greater precision. If the calculated speeds were quite different from one trial to the next, the precision is low.) If you are unsure about the difference between precision and accuracy, review the meanings of these terms in Skill Set 1.

2. Compare the values of the speed of the wave for the two different methods. Do the ranges of values of speed for the two methods overlap? Are the values of average speed of the wave similar or quite different for the two different methods?

3. List the factors that might have contributed to any lack of compatibility of the two methods.

4. From your observations and analyses, which average speed do you think is the most accurate? Explain the reasoning on which you based your conclusion.

5. What is the relationship between the natural frequencies of the spring and its fundamental frequency?

6. How could you tell if you had missed one of the natural frequencies when you were finding natural frequencies above the fundamental?

Standing wave patterns can be set up in a variety of objects. If you carefully examine the photograph of the Tacoma Narrows Bridge collapse on page 336, you should see evidence of the standing wave that was set up in the bridge. You can also observe standing wave patterns in the radio antenna of a car as you travel at different speeds along a highway.

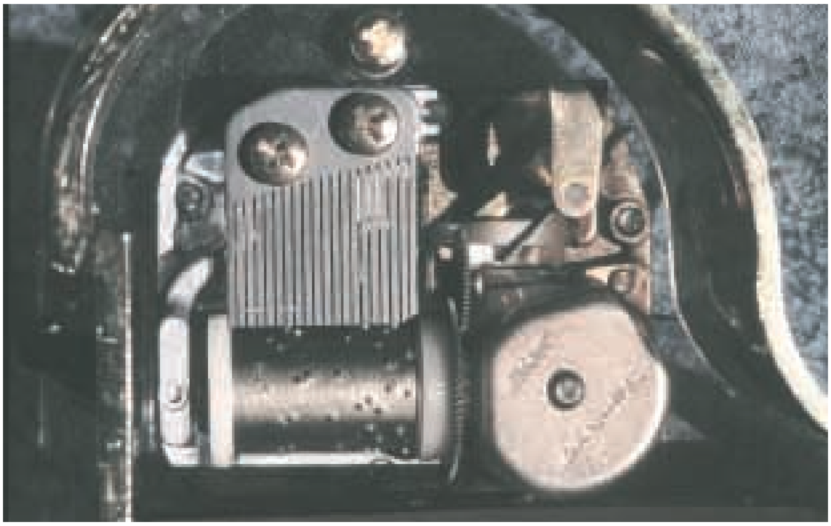


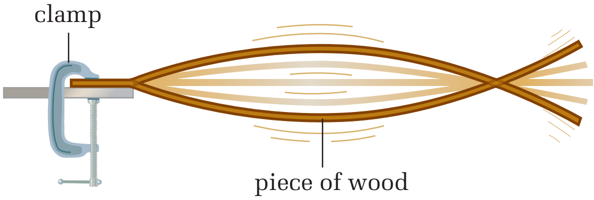
Figure 8.20 The tones of a music box are created by the natural frequencies of tiny strips cut from a small sheet of metal. As the drum turns, pegs on the drum flip the metal strips and cause them to vibrate.

QUICK LAB Standing Waves in a Thin Piece of Wood

TARGET SKILLS

- **Analyzing and interpreting**
- **Communicating results**

Standing wave patterns can easily be set up in a long piece of wood moulding. Obtain a piece of quarter-round moulding 2 m to 3 m long and 0.50 cm thick. With the moulding oriented horizontally or vertically, vibrate one end of the moulding back and forth through a range of frequencies. You should be able to "feel" the resonance that is produced when you are vibrating the moulding at a natural frequency.



How is the wavelength associated with the fundamental frequency related to the length of the moulding?

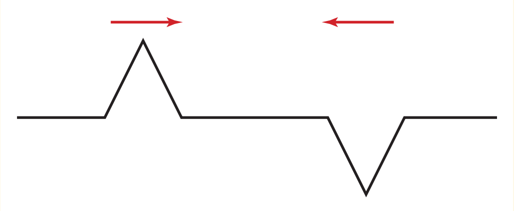
Analyze and Conclude

1. How do the standing wave patterns produced in the moulding differ from those produced in the spring?
2. Describe the standing wave pattern produced by the fundamental frequency.

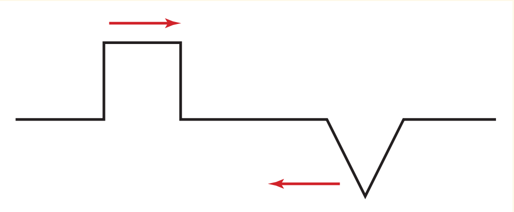
8.3 Section Review

1. **K/U** Two triangular pulses, each 2 cm high and 1 cm wide, were directed toward each other on a spring, as shown. Sketch the appearance of the spring at the instant that they met and completely overlapped. What kind of interference is this?

2. **K/U** Two triangular pulses, each 2 cm high and 1 cm wide, were directed toward each other along the same spring. However, the pulse approaching from the left was upright and the one approaching from the right was inverted. Sketch the appearance of the spring at the instant that the two pulses met and completely overlapped. What kind of interference is this?



3. **K/U** An upright square pulse and an inverted triangular pulse were directed toward each other on a spring, as shown in the illustration. Sketch the appearance of the spring at the instant the two pulses met and completely overlapped. What principle did you use in constructing the shape of the spring for the instant at which the two pulses met? What does this principle state about how waves combine?

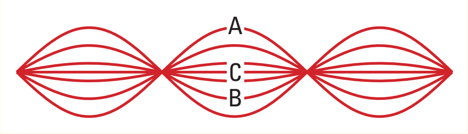


4. **C** Describe what you would see when a standing wave was set up in a spring. Why is it called a standing wave?

5. **K/U** What is a node? What is an antinode? Describe how the nodes and antinodes are distributed along the length of the standing wave pattern.

6. **C** Sketch the appearance of the standing wave pattern set up in a spring when it is fixed at one end and the other end is vibrated at (a) its fundamental frequency, (b) a frequency twice its fundamental frequency, and (c) a frequency three times its fundamental frequency.

7. **K/U** The figure shown here represents a spring vibrating at its second overtone. The points labelled (A), (B), and (C) represent the location of the central point of the string at various times.



(a) At which location is the central point of the string moving at its maximum speed?

(b) At which location is its instantaneous speed zero?

(c) At which location is the point on the string moving with an intermediate speed?

(d) Explain the reasoning you used to answer the above questions.