Chapter 11

Waves

11.1 Observations: Pulses and wave motion

OALG 11.1.1 Observe and explain

Equipment: a pond or a large bowl, a small object to drop, a smartphone.

Go to a nearby pond, find a small rock (the smaller, the better), drop it into the pond, and video what happens. You can do it at home too if you have a large bowl. In case doing your own experiment is impossible, observe the following high-speed video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-1-3].

Devise two (or more) explanations as to how the disturbance created by the falling droplet spreads outward. What experiments can you design to test these explanations?

OALG 11.1.2 Test your ideas

Use the explanations from Activity 11.1.1 to predict what will happen to pieces of light Styrofoam if we place them on the surface of the water before we drop the rock. Write the predictions down, and then observe the following high-speed video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-1-4]. Compare your predictions to the outcomes. Which of your explanations devised in Activity 11.1.1 can be rejected?

OALG 11.1.3 Explain

Based on your observations and reasoning, what is necessary for you to observe a wave? What property of the medium is essential for wave propagation? After you answer these questions, read and interrogate material on page 316 in the textbook (do not forget to watch the video!). Do your ideas agree with the ideas you read in the textbook? Explain.

OALG 11.1.4 Read and interrogate

Read and interrogate the rest of Section 11.1 and answer Review Question 11.1.

11.2 Mathematical descriptions of a wave

OALG 11.2.1 Observe and explain

Open the PhET simulation using the following link:

https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html

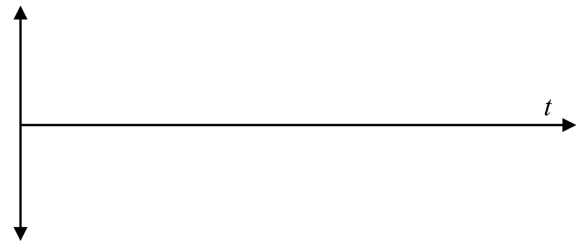
Set damping to "none", set tension to "low", select "no end", and select "oscillate".

Now, set the frequency to 0.5 Hz, and check "rulers" and "timer". You're all set to go.

a. Start vibrating the string by hitting "restart." Look at the wave as it propagates down the string. Use the "slow motion" function if it helps. As accurately as possible, describe the motion of the disturbance in words. What type of motion is it (constant speed/constantly speeding up)?

b. If you hit the pause button, you're now looking at a picture of the disturbance at an instant in time (a single snapshot of the action). Based on this snapshot, construct a graph that shows (on the vertical axis) how the medium is disturbed at that instant of time at different positions *x* along the horizontal axis. (Think carefully about what physical quantity you want to put on the vertical axis.)	

c. Start oscillating the string again by hitting "restart." Now, pick one of the green dots on the string and focus your attention on it. Describe the motion of the green dot in words and draw a rough motion diagram for that dot.

d. Based on your observations construct a graph that shows how the green dot moves as a function of time. (Think carefully about what physical quantity you want to put on the vertical axis.)	

e. Now, try varying the frequency of the oscillation up to about 1 Hz. Does the speed at which the wave moves down the string depend on how fast the end is oscillating up and down? Describe what happens to the whole wave when the frequency is increased. Explain why this happens.

OALG 11.2.2 Represent and reason

Open the PhET simulation at the following link:

https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html

Set damping to "none", set tension to "low", select "no end", and select "oscillate".

Now set the frequency to 0.5 Hz, check "rulers" and "timer". You're all set to go.

a. Hit "restart" and observe the motion of every other green dot. As clearly as possible, describe what you see related to the relationship between the motions of the green dots.

b. Construct a displacement-versus-time graph for one green dot on the string. Show the period T of that dot's motion on your graph. (If the frequency is 0.5 Hz, what is the period?)

c. Pause the simulation and construct a displacement-versus-position graph for a segment of the infinitely long string. Show the green dots, and number them 1, 2, 3, etc. Green dot number 1 is the one attached to the oscillator. What name shall we give to the distance between every other green dot?

d. Pause the simulation, hit "restart", and use "slow motion." Now, let the simulation run. How long does it take for the front of the disturbance to get from dot 1 to dot 3? How long does it take for the front of the disturbance to get from dot 1 to dot 5? Step the simulation one frame at a time if needed.

e. If the disturbance moves down the string at a constant speed v, come up with a mathematical relationship that relates the distance λ *between every other green dot* to the period T of the oscillator and the speed v of the wave.

OALG 11.2.3 Reason

The frequency f of a wave equals $1/T$ where T is the period of one full vibration of a point of a medium in which the wave propagates.

a. Suppose that there are 10 vibrations in 5 s. What is the frequency of such a wave, and what is its period?

b. If the wave travels at speed 4.0 m/s, how far will it travel during one period?

c. Show that the wavelength can be written as $\lambda = v/f$.

OALG 11.2.4 Represent and reason

The goal of this activity is to construct a mathematical representation that describes the motion of the wave on a string.

Open the PhET simulation at the following link:

https://phet.colorado.edu/sims/html/wave-on-a-string/latest/wave-on-a-string_en.html

Set damping to "none", set tension to "low", select "no end", and select "oscillate".

Now set the frequency to 0.5 Hz, check "rulers" and "timer". You're all set to go.

a. The motion of the green dot attached to the oscillator can be described by the function:

$$y_{\text{at } x=0} = A\cos\left(\frac{2\pi}{T}t\right)$$

The motion of another point on the string at a distance x from the starting point can be described as the same motion as the point at $x = 0$, but with a time delay t_0. Write t_0 in terms of x, the distance from the origin, and v, the speed at which the wave travels down the string.

b. If we want to describe the motion of the string at any point x using the same clock that we used for the point $x = 0$, we need to factor a time delay into the function like so:

$$y_{\text{at } x} = A\cos\left(\frac{2\pi}{T}(t \pm t_0)\right)$$

Decide whether you should add t_0 or subtract t_0 to describe the y motion of a point x. Remember, this point is making exactly the same motion as the point at $x = 0$, but t_0 *after* the point at $x = 0$. After you have decided, rewrite the function above with the correct sign for t_0 and use the expression you found for t_0 in part **a.**

c. The second green dot to the right is a special point because it executes exactly the same motion as the green dot attached to the driver. What is the time delay between the motion of the driver green dot and the second dot to the right?

d. Write the distance between $x = 0$ and the second green dot in terms of the wave speed v and the time you found in part **c.** Use this to rewrite the function you arrived at in part **b.** You should now have a general mathematical function describing for the motion of a wave.

e. Compare the function you devised to Equations 11.2 and 11.4 on pages 320 and 321 in the textbook.

OALG 11.2.5 Describe and explain

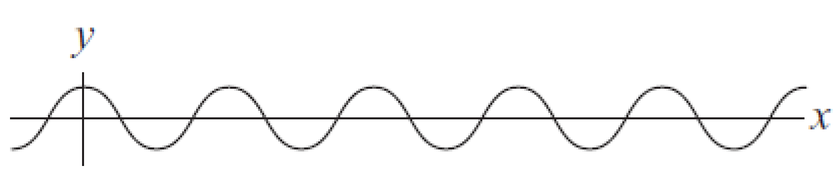
A periodic wave disturbance created by a sinusoidally vibrating source at one particular time (call it $t = 0$) is represented by the graph below. In a way, the graph is a snapshot of the wave. Your physics major friend claims that the function that follows describes this periodic wave disturbance at different positions x at different times t:

$$y(t,x) = A\cos\left(\frac{2\pi}{T}t - \frac{2\pi}{\lambda}x\right)$$

where y is the disturbance at time t of the medium at position x (the distance from the source).

First, examine the function and decide whether it makes sense. How is the function similar to the mathematical function describing SHM? How is it different?

Answer the following questions to test her claim. Note that A is the amplitude of the wave, T is its period, and λ is its wavelength.



a. Without looking at the function, answer the following questions: At $t=0$ and $x=0$, a particular wave disturbance has a value $y = A\cos 0 = A$, which matches with what we see in the figure above. At the same time $(t=0)$, what should the value y of the disturbance be at one wavelength forward? What will it be at two wavelengths forward? Three wavelengths forward? Now, compare your answers to the answers predicted by the function above. Does the function give you the desired value? Explain.

b. Without looking at the function, answer the following questions: At $t=0$, what should the value y of the wave disturbance be at positions $x=\lambda/2,\ 3\lambda/2,\ 5\lambda/2,$ and so forth? Now, compare your answers to the answers predicted by the function above. Does the function give you the desired values? Explain.

c. At $t=0$, what will the value y of the wave disturbance be at positions $x=\lambda/4,\ 3\lambda/4,\ 5\lambda/4,$ and so forth? Does the function give you the desired value? Explain.

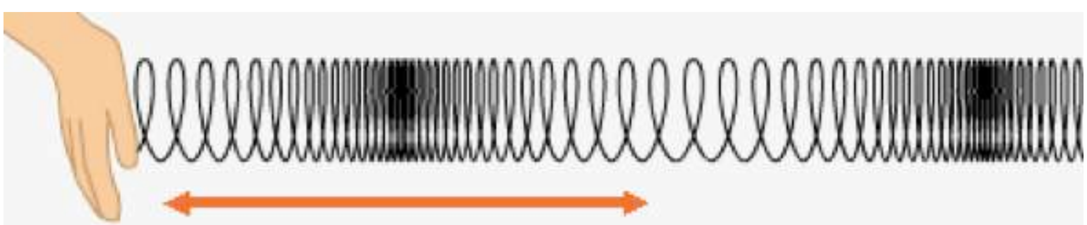
d. At $t=T$, what will the value of y be at positions $x=0,\ \lambda/4,\ \lambda/2,\ 3\lambda/4,$ and λ? Does the function give you the desired values? Explain.

e. Does the mathematical description seem appropriate based on your analysis? Explain.

11.2.6 Practice

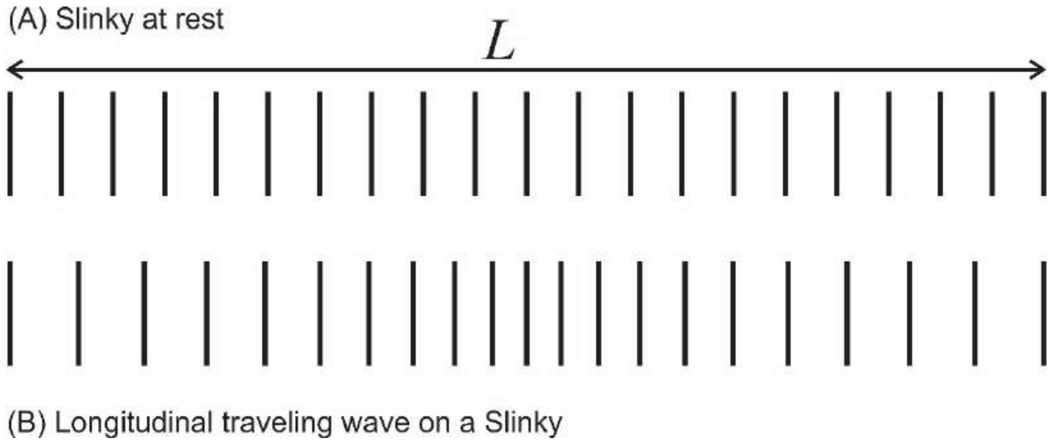
Solve Problem 3 on page 347 in the textbook.

11.2.7 Represent and reason



Observe a longitudinal pulse on a Slinky placed on the floor. How do the individual coils move when the pulse propagates?

The figure below shows part of a Slinky of length L at rest (A) and a snapshot of the same part of the Slinky while the *longitudinal* wave is moving along the slinky (B).



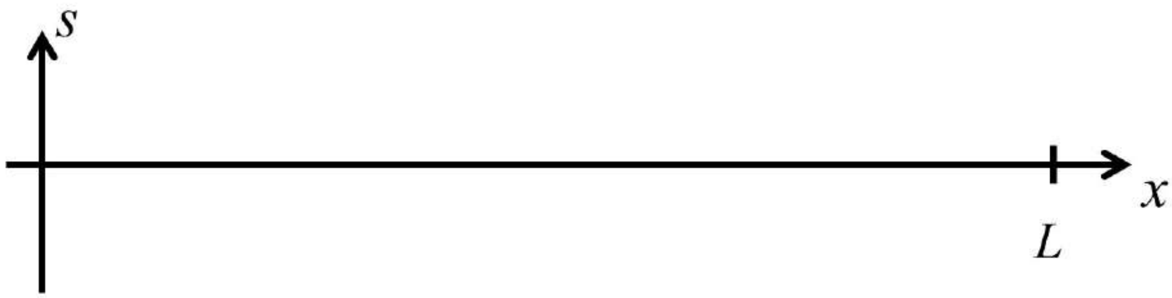
a. In the space between figures A and B, draw arrows that represent the displacement of each coil in figure A needed to bring it to the corresponding position in figure B.

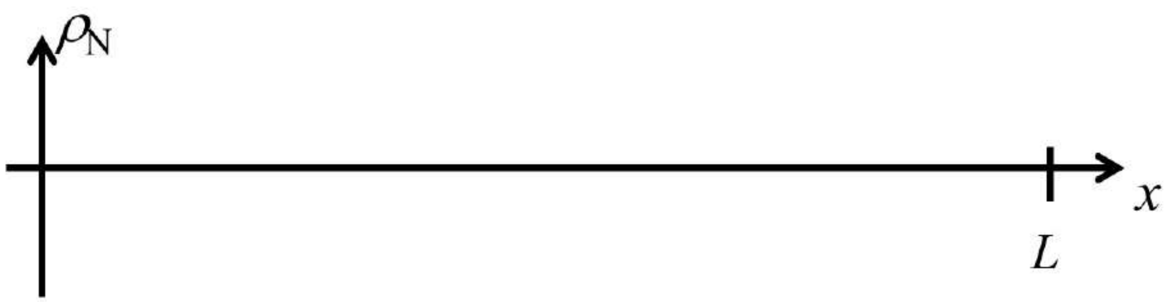
b. Draw a qualitative position-versus-displacement graph $s(x)$ that shows how the displacement of a particular coil in a longitudinal wave on a Slinky depends on the initial position of that coil on the Slinky at rest. Assume that the *s* axis points to the right. Represent the dependence on the graph with a continuous curve. What is the wavelength of the wave?

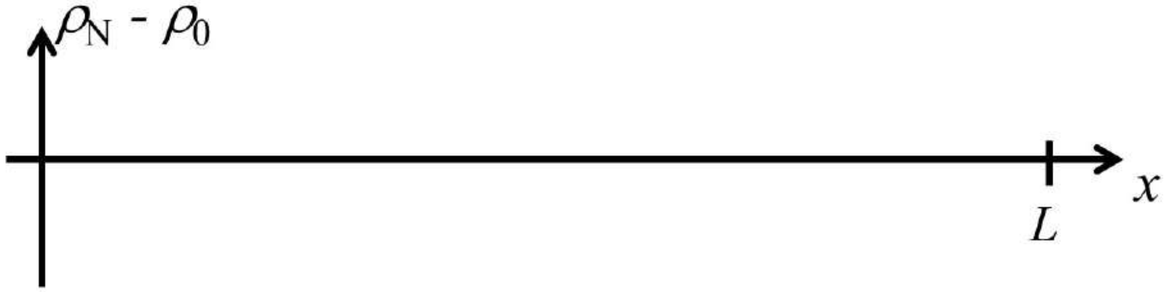
c. Let's define a new physical quantity that describes how many turns per unit length are in a short segment of a Slinky. We will call this quantity a *density of turns* and denote it with ρ_N. Draw a qualitative graph $\rho_N(x)$ that shows how the density of turns in a traveling longitudinal wave depends on the position along the Slinky. Represent the dependence with a continuous curve.

e. Let ρ_0 be the density of turns of a Slinky at rest. Draw a qualitative graph $\rho_N(x) - \rho_0$ that shows how the *change* in density of turns (with respect to the Slinky at rest) in a traveling longitudinal wave depends on the position along the Slinky. Represent the dependence with a continuous curve.

f. Compare and contrast the graphs $s(x)$ and $\rho_N(x) - \rho_0$ that you obtained in steps b. and e. Describe any differences and similarities.







OALG 11.2.8 Read and interrogate

Read and interrogate Section 11.2 in the textbook and answer Review Question 11.2.

OALG 11.2.9 Practice

Answer Questions 2 – 5, 8, and 12 on page 346 and solve Problems 1 and 2 on page 347 in the textbook.

11.3 Dynamics of wave motion: Speed and the medium

11.3.1 Observe and explain

Imagine that you have three long springs. If you measure the speed of transverse wave pulses along the springs, you would accumulate the data given in the following table.

Spring number	Force exerted on the end of the spring (tension, N)	Amplitude (cm)	Frequency (Hz)	Mass/length (kg/m)	Speed (m/s)
1	4.0	10	2	0.16	5.0
1	8.0	10	2	0.16	7.1
1	16.0	10	2	0.16	10.0
1	4.0	10	2	0.16	5.0
1	4.0	20	2	0.16	5.0
1	4.0	30	2	0.16	5.0
1	4.0	10	2	0.16	5.0
1	4.0	10	3	0.16	5.0
1	4.0	10	4	0.16	5.0
1	4.0	10	2	0.16	5.0
2	4.0	10	2	0.080	7.1
3	4.0	10	2	0.040	10.0

a. Come up with an expression that can be used to determine the speed of the wave as a function of different properties of the springs. Explain how you came up with your expression using the data in the table. Evaluate the units and extreme cases. Does your expression pass the evaluation?

b. Compare and contrast your expression with Equation 11.5 on page 323 in the textbook. Read and interrogate Section 11.3.

11.3.2 Represent and reason

Two ropes have the same length. The speed of a pulse on rope 1 is 1.4 times the speed on rope 2.

Write an expression for the ratio of the speeds (v_1/v_2) in terms of the ratios of the rope tensions (F_1/F_2) and of the rope masses (m_1/m_2). Do not use numbers yet.	If the forces pulling on the ends of the rope (the rope tensions) are the same, determine the ratio of the rope masses for the speed ratio given in the problem statement.	If the masses of the ropes are the same, determine the ratio of the forces pulling on the ends of the ropes—for the speed ratio given in the problem statement.

11.3.3 Reason

The speed of a wave depends on properties of the medium through which the wave travels. The speed v can also be determined in a different way—if you know the wavelength λ of the wave and the period T of the vibration, then $v = \lambda/T$.

a. Explain why this equation makes sense. Does the speed actually depend on the wavelength or period?

b. Is the equation $v = \lambda/T$ an operational definition or a cause-effect relationship for the wave speed? Explain. (To review what is an operational definition and what is a cause-effect relationship, review the material on page 64 in the textbook.)

11.3.4 Represent and reason

Waves are commonly described using four physical quantities: (1) amplitude A, (2) frequency f, (3) wave speed v, and (4) wavelength λ. Indicate how you would define these four quantities. Illustrate your definitions with reference to the pictures and graphs in previous activities. What types of change(s) in the source or in the medium would lead to a change in each of these quantities? Create a table like the one that follows.

For help, use Sections 1-3 in Chapter 11 in the textbook.

Quantity	**Write a definition of the quantity.**	**Illustrate your definition of the quantity.**	**Does quantity depend on the source or the medium? Explain why.**

Amplitude			
Frequency			
Wave speed			
Wavelength			

OALG 11.3.5 Practice

Solve problems 14, 18, and 19 on page 347 in the textbook.

11.4 Energy, power, and intensity of waves

11.4.1 Read and interrogate

Work through Section 11.4 on your own, solve Quantitative Exercise 11.3, and answer Review Question 11.4.

11.5 Reflection and impedance

OALG 11.5.1 Observe and find a pattern

Observe the video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-5-1] and find patterns in the behavior of the waves when being reflected off a fixed end (the boundary with a more dense medium) and off an end connected to a string (the boundary with a less dense medium). How do the relative densities of the two media affect the reflection? Explain your observations.

11.5.2 Observe and explain

Watch the video in Activity 11.5.1.

Analyze both experiments by using an energy and momentum approach and by using the questions below. The system is the Slinky.

a. A transverse pulse is traveling along the Slinky. What types of energies are present in the Slinky?

b. Assume that we neglect the frictional forces between the Slinky and the floor and any air drag. For any of the two experiments described above, can we say that the total energy of the Slinky is constant through the whole experiment? Explain.

c. A transverse pulse is traveling along the Slinky. Which parts of the Slinky have a non-zero momentum? Explain. What is the total momentum of the Slinky (before the pulse reaches the end of the Slinky)? Explain.

d. Assume that we neglect the frictional forces between the Slinky and the floor and any air drag. For any of the two experiments described above, can we say that the total momentum of the Slinky is constant through the whole experiment? Explain.

11.5.3 Read and interrogate

Read and interrogate Section 11.5 and answer Review Question 11.5.

OALG 11.5.4 Practice

Solve Problems 27, 29, and 30 on page 348 in the textbook.

11.6 Superposition principle and skills for analyzing wave processes

OALG 11.6.1 Observational and explain

a. Go to [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-6-1]. Observe and describe what happens. What do you see when two pulses coming from opposite directions meet?

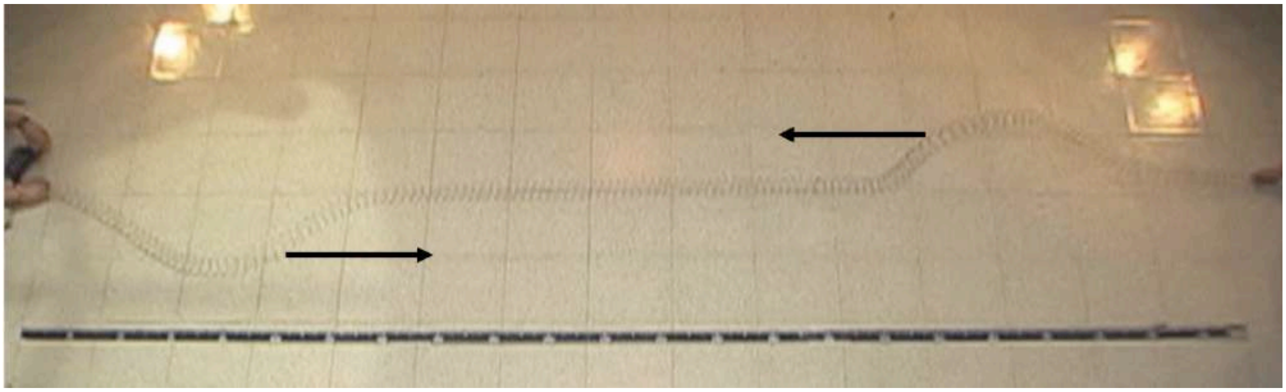
b. Brainstorm one or two ideas to explain what is happening when the two pulses meet each other.

c. If you come up with two competing ideas as to what happened, brainstorm ways in which you could conduct a testing experiment to decide which of these two ideas is correct.

OALG 11.6.2 Test your ideas

Before you watch the video, answer the following questions:

In this video, two oppositely oriented pulses approach each other from opposite directions as shown in the snapshot below:

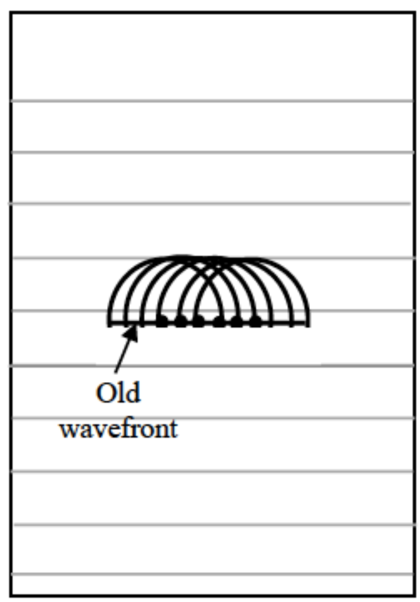


a. Use each explanation you developed in Activity 11.6.1 part **b.** to make a prediction about what the Slinky will look like just *after* the two pulses meet. (One prediction based on each explanation.) Sketch them in your notebook.

b. Now that you have sketched out your predictions, watch the following video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-6-2] to see which explanation best explains the behavior in this video. (Which prediction was consistent with the actual outcome of this experiment?)

c. How can it be that two pulses arrive to the same place at the same time and the spring appears to be flat? Where did the energy of the system go in the instant when the spring is flat?

d. Watch the following video at [https://youtu.be/XUPHgm9dLIE]. Is the outcome consistent with the explanation you chose in part **b**?

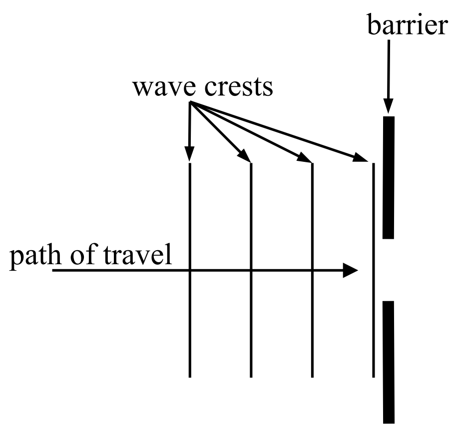


OALG 11.6.3 Represent and reason

Christian Huygens, a contemporary of Newton, wondered what happened if several waves simultaneously traveled through a medium. To answer this question, let's try an experiment similar to that used by Huygens. We mark six dots across a page, each dot separated by 1 cm from the adjacent dot (see the illustration at right). The dots represent points on the crest of a wave moving toward the top of the page. According to Huygens, each dot causes a small circular wave disturbance that moves up the page in the direction the wave is traveling. In the figure, the 3-cm radius half circles, called *wavelets*, represent these disturbances. Create a similar diagram in your notebook. Note places above the dots where the net disturbance from the six wavelets is two or more times bigger than the disturbance caused by any one wavelet (i.e., places where the wavelets add together to form a bigger wave). This is the new crest of the wave. Draw a line on your sketch indicating the location of the *new* wave crest. Also, draw a ray indicating the direction the wave is traveling. The pattern would be even clearer if you added many more dots and wavelets in the same space.

OALG 11.6.4 Test an idea

Test Huygens' wavelet idea. In the following video experiment, a flat water wave travels toward a narrow gap, as shown in the diagram below. Use Huygens' idea to predict what will happen if a wave passes through the narrow gap. Start by drawing a wave crest *in* the gap. Then draw wavelets coming from that wave crest (make them big) to find the shape of the next wave crest (draw it). Now, do it again to find the next wave crest, and then do it a third time. Pay attention to the edges of your wave crest. Then watch the video: [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-6-4]. Did the outcome match your prediction? What can you conclude about Huygens' idea?



OALG 11.6.5 Observe and explain

Watch the video of a sea wave passing through the slits between the rocks [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-6-5]. Describe your observations and explain the existence of locations where the water is not being disturbed despite the waves passing through these locations. Use the guiding questions below to help you explain what you're seeing.

Note that on the diagram at right, "C" stands for crest and "T" stands for trough.

a. Indicate with the letter "dc" (double crest) places along line 0 that are equidistant from the wave sources and where the crests add to form a disturbance that is twice as big as the wave amplitude from one source.

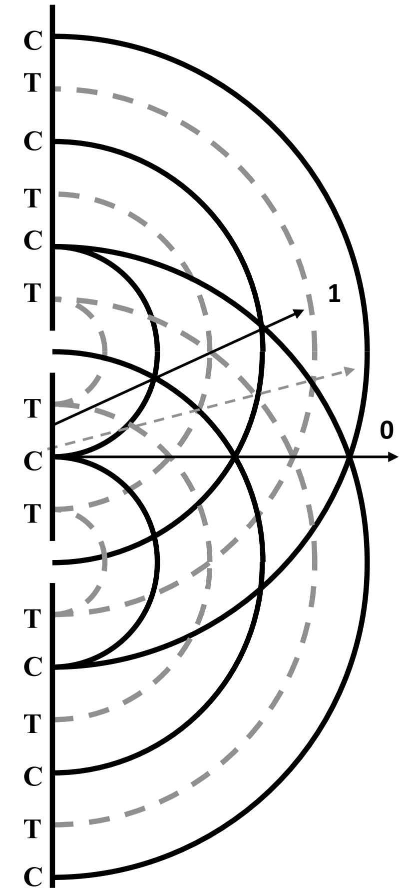
b. Indicate with the letter "dt" (double trough) places along on line 0 that are equidistant from the sources and where the wave troughs add to form a negative disturbance that is twice the negative amplitude of a wave trough from one source.

c. The sketch represents the positions of wave crests and troughs at one particular time. Suppose that these are water waves that are now moving. Also suppose that you float in the water on the right side of the waves along line 0 passing through the alternating dc and dt points. What would it feel like if you were floating there?

d. Would you feel the same thing if you were floating somewhere along line 1 as along line 0? Explain.

e. What would it feel like if you were floating at the end of the grey dashed line between 0 and 1? Explain why.

f. On the diagram, indicate one more line of constructive interference and two more lines of destructive interference.



OALG 11.6.6 Regular problem

Solve the problem below using the steps of the problem solving strategy in the table. Then compare your solution to the solution in Example 11.4 in the textbook.

Two sound speakers separated by 100 m face each other and vibrate in unison at a frequency of 85 Hz. Determine three places on a line between the speakers where you cannot hear any sound.

Sketch and translate	

• Sketch the situation. Label all known quantities. • Label the unknown quantities.	
Simplify and diagram • Decide what simplifying assumptions you should make. • Draw displacement-versus-time or displacement-versus-position graphs to represent the waves if necessary.	
Represent mathematically • Represent the problem using mathematical relationships between physical quantities.	
Solve and evaluate • Solve the equations for the unknown quantity. • Evaluate whether the results are reasonable (the magnitude of the answer, its units, how the solution behaves in limiting cases, and so forth).	

OALG 11.6.7 Represent and reason

In multiple ways, describe a traveling wave on a very long string. The period of the wave is 0.20 s, the amplitude is 6.0 cm, and the wavelength is 4.0 cm. Make sure you use consistent units.

a. Determine the wave's frequency and speed.

b. Construct a displacement-versus-time graph for one point on the string.

c. Construct a displacement-versus-position graph for one particular time.

d. Write the displacement as a function of position and time.

OALG 11.6.8 Read and interrogate

Read and interrogate Section 11.6 and explain Huygens principle in your own words. What every-day phenomena can be explained using Huygens principle?

OALG 11.6.9 Practice

Solve Problems 31 and 34-36 on page 348 in the textbook.

11.7 Sound

OALG 11.7.1 Observe and explain

Equipment: different musical instruments (any instruments that you have available at home), the Phyphox app on your phone, wine glass, and a fork.

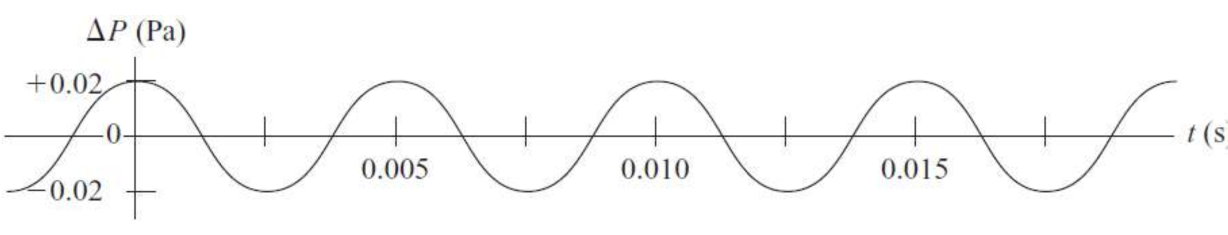
Open the Audio Scope in your Phyphox app. Examine the empty graph that appears on the screen. Note that the vertical access reflects the air pressure, not the amplitude.

a. Press the play button and create different sounds by singing a note or whistling. Observe the differences in the shape of the graph. Explain why the differences occurred. Are you able to produce a sinusoidal sound?

b. Use a wine glass, hold it by the stem and lightly strike it with a fork. Listen to the tone of the sound it produces. Record the sound with the Audio Scope. Add a little bit of water to the glass and repeat. What happened to the sound? Keep adding water and listening to the sound. How can you explain the change in the frequency? Hint: think of the vibrating glass with water in it as an object attached to a spring. What happens to the frequency of vibrations when you increase the mass of the object?

OALG 11.7.2 Reason

The graph below describes the varying air pressure against a microphone as a sound wave passes. The readings are given with respect to the atmospheric pressure when the sound is not present. The negative pressure means that the pressure at a particular time is less than atmospheric pressure. Answer the following questions. *Note:* Sound travels at about 340 m/s and $1\ \text{Pa (pascal)} = 1\ \text{N/m}^2$.



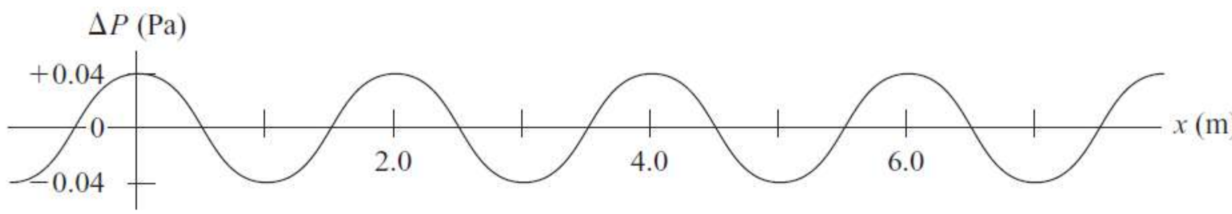
a. Determine the amplitude of the wave.

b. Determine the frequency of the wave.

c. Determine the wavelength of the wave.

OALG 11.7.3 Reason

The graph below describes the varying air pressure at different positions in space at one particular time due to a sound wave. Answer the following questions. Again, remember that sound travels at about 340 m/s.



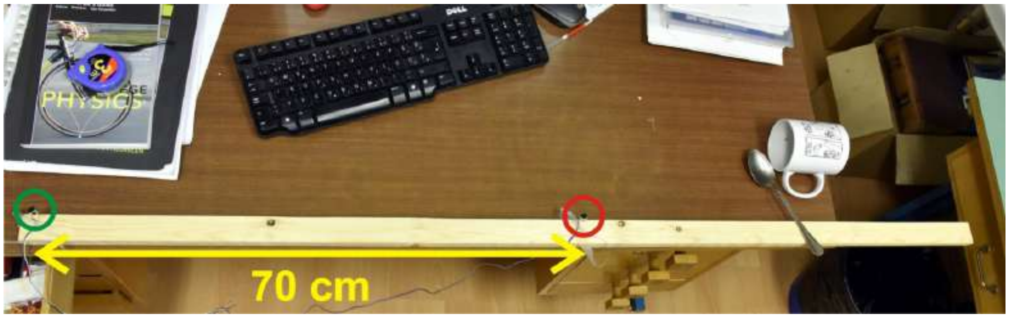
a. Determine the amplitude of the wave.

b. Determine the wavelength of the wave.

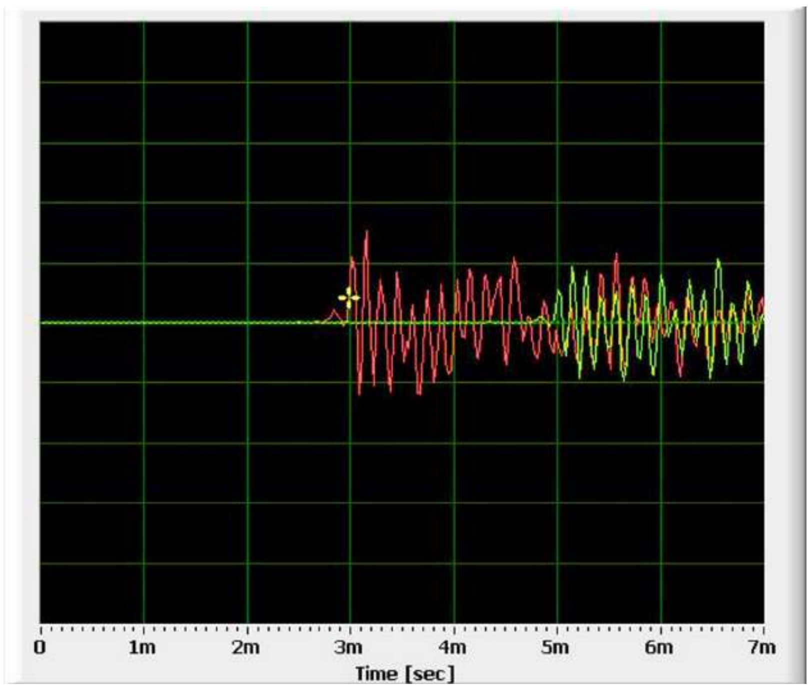
c. Determine the frequency of the wave.

OALG 11.7.4 Observe and analyze

We placed two microphones 70 cm apart and fixed them to a wooden plank with an adhesive tape. A computer soundcard captures sound detected by each microphone and displays it on an oscilloscope-like screen. The signal from the right microphone is represented with a red curve and the signal from the left one is represented with a green curve. The program for capturing the signal was set in a way that it started recording signals from both microphones when the signal detected by the right (red) microphone rose above a certain value.
The experimental setup is shown in the figure below (each microphone is circled with a color that correspond to the color of the signal trace on the screen):



Experiment We held a mug somewhere close to the right end of the wooden plank (without touching the plank) and hit the mug with a spoon. The recorded signals are shown in the figure below. On the vertical axis you see the pressure and on the horizontal axis you see the time in milliseconds (m stands for milli).



What can you determine from the data collected in this experiment? Make a list of physical quantities and determine each of them.

OALG 11.7.5 Reason

The mathematical representation that follow describe the variation of pressure at different positions and times (relative to atmospheric pressure) caused by sound waves. Fill in the table that follows. *Note:* The speed of sound in air is 340 m/s.

Mathematical representation

$\Delta P = (2.0\ \text{N/m}^2)\cos\left(2\pi\left(\frac{t}{0.010\ \text{s}} - \frac{x}{3.4\ \text{m}}\right)\right)$			
Identify the amplitude of the pressure variation.	Identify the period for one vibration.	Determine the frequency of the sound.	Identify the wavelength of the sound.
Mathematical representation $\Delta P = (4.0\ \text{N/m}^2)\cos\left(2\pi\left(\frac{t}{0.0010\ \text{s}} - \frac{x}{0.34\ \text{m}}\right)\right)$			
Identify the amplitude of the pressure variation.	Identify the period for one vibration.	Determine the frequency of the sound.	Identify the wavelength of the sound.

OALG 11.7.6 Read and interrogate

Read and interrogate Section 11.7 in the textbook and answer Review Question 11.7.

OALG 11.7.7 Practice

Solve Problems 41 and 43 on pages 348-349 in the textbook.

11.8 Standing waves on strings

OALG 11.8.1 Observe and find a pattern

Watch the video at [https://mediaplayer.pearsoncmg.com/assets/_frames.true/secs-experiment-video-50]. In the experiment, one end of the rope is attached to a wall and the other end is being shaken by Eugenia. As she slowly increases the frequency of shaking, one point of the rope stops moving and the other two points (each half the wavelength from the stationary points) move with the largest amplitude.

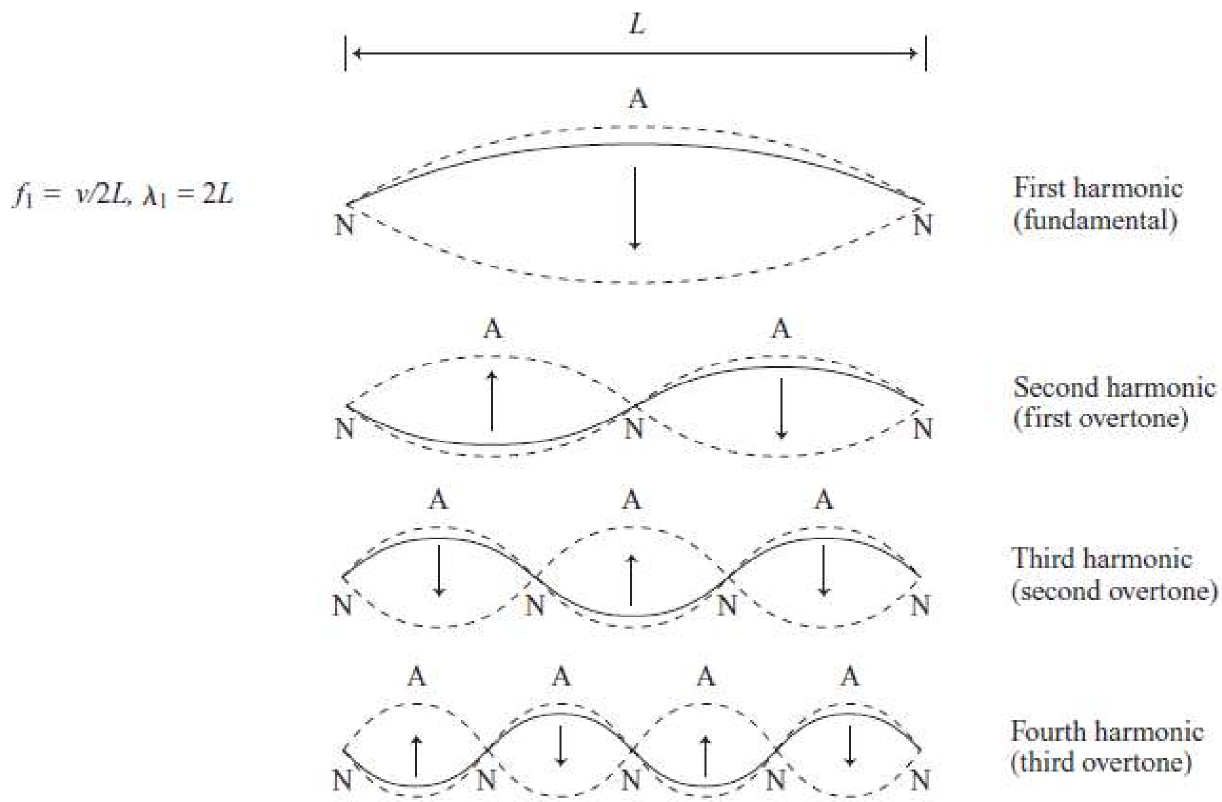
a. In the figure below, identify the situation recreated in the video. Read and interrogate Observational Experiment Table 11.5 on page 336 in the textbook to learn how Eugenia created this new type of wave – the standing wave.

b. If Eugenia continued to increase the frequency, she would be able to recreate the rest of the pictures below. By looking at the shapes of the standing waves, write down expressions for the wavelengths of each of the observed standing waves in terms of *L*, the length of the Slinky.

c. Write a general expression for the wavelength of any possible standing wave vibration in terms of a positive integer *n*. In other words, what is the wavelength of the *n*th harmonic?

d. Use the wavelengths you observed from part **b.** to write expressions for the frequencies of three other possible standing-wave vibrations that are not shown in the figure below.

e. Write a general expression for the frequency of any possible standing wave vibrations in terms of a positive integer *n*. In other words, what is the frequency of the *n*th harmonic? Compare your work to Equation 11.11 on page 337.



OALG 11.8.2 Evaluate the solution

A friend proposes a solution for the following problem.

The problem: A violin A string is 0.33 m long and has mass 0.30×10^{-3} kg. It vibrates at a fundamental frequency of 440 Hz (concert A). What is the tension in the string?

Proposed solution: Speed depends on the tension and string mass as $v = \sqrt{\frac{T}{m}}$. Thus,

$$T = v^2 m = (340 \text{ m/s})^2 (0.30 \text{ g}) = 34{,}680 \text{ N}$$

a. Evaluate the solution and identify any errors.

b. Provide a corrected solution if you find errors.

OALG 11.8.3 Apply

You can make a simple string instrument by wrapping a rubber band around an empty tuna can (see figure on the right; make sure the edges of the can are not sharp). The high-speed video [https://mediaplayer.pearsoncmg.com/assets/_frames.true/sci-phys-egv2e-alg-11-8-6] shows the vibrations of a rubber string on an 85-mm diameter tuna can, recorded at 1200 frames per second. Watch the video and make a list of physical quantities that you can determine based on the video. Then determine their values. Indicate any assumptions that you made and include the uncertainties for your values.

OALG 11.8.4 Summarize

Read and interrogate Section 11.8 in the textbook and, in your own words, describe the similarities and differences between traveling waves and standing waves.

OALG 11.8.5 Practice

Solve Problems 51, 59-61, and 79 on pages 349-350 in the textbook.

11.9 Standing waves in air columns

OALG 11.9.1 Explain

Equipment: recorder or a whistle.

Wind instruments such as trumpets, flutes, clarinets, and the pipes in organs consist of columns of air inside tubes. They also have opening and closing valves (or slides, in the case of a trombone).

a. Explain how the valves and slides allow a musician to change the frequency of sound that these instruments produce.

b. Blow a whistle and try to change the frequency of sound it produces. How did you do it? Is the reason consistent with the explanation you provided in part **a**?

c. Read and interrogate Section 11.9 in the textbook. Compare and contrast your answer in part **a** to the answer you find when reading this section.

OALG 11.9.2 Represent and reason

Read the descriptions of the situations described below and answer the questions that follow.

Situation I: A 0.50-m-long string vibrates in three segmentswith a frequency of 240 Hz.

Situation II: A 0.68-m pipe is open at both ends. The speed of sound is 340 m/s.

a. What is the fundamental frequency of the string?

b. What is the speed of a wave on this string?

c. What is the fundamental frequency of the pipe?

d. What is the fundamental frequency of the pipe when one end is closed?

OALG 11.9.3 Evaluate the solution

The problem: A shepherd blows on the end of a bone pipe (it is considered closed at one end and open at the other) that is 0.30 m long. She can play the first harmonic by blowing gently and higher harmonics by blowing harder. Determine the frequencies of the first three harmonics.

Proposed solution: The speed of sound in the solid bone material is about 3000 m/s. In air, it is about 340 m/s. Thus, the first three harmonic frequencies are:

$$f_1 = v/2L = (3000\text{ m/s})/\left[2(0.30\text{ m})\right] = 5{,}000\text{ Hz}$$

$$f_2 = 2v/2L = 2(3000\text{ m/s})/\left[2(0.30\text{ m})\right] = 10{,}000\text{ Hz}$$

$$f_3 = 3v/2L = 3(3000\text{ m/s})/\left[2(0.30\text{ m})\right] = 15{,}000\text{ Hz}$$

a. Identify any errors in the solution to the problem.

b. Provide a corrected solution if there are errors.

OALG 11.9.4 Apply

You form a palm-pipe band where the musicians initiate sounds (fundamental frequencies) by hitting one end of a tube with their palm (see the photo on the right). Your band wants to play songs with notes ranging in frequency from 120 Hz to 300 Hz. There are two ways to initiate the sound: (1) by hitting the end of the tube and quickly removing the hand from it or (2) by hitting the end of the tube and keeping the hand on it.

a. How do the two ways of initiating the sound affect the sound produced by a particular tube?

b. Determine the length of the palm-pipe to play a 120-Hz sound. Explain how you arrived at your answer.

c. Determine the maximum length of the palm-pipe that can play a 300-Hz sound.

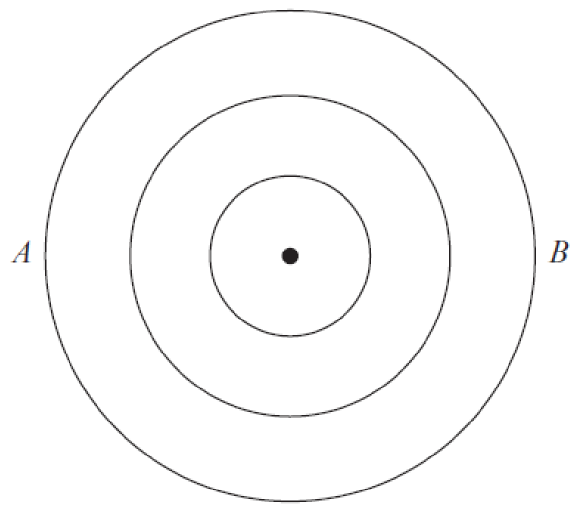
OALG 11.9.5 Practice

Solve Problems 56, 58, and 63-64 on page 349 in the textbook.

11.10 The Doppler effect

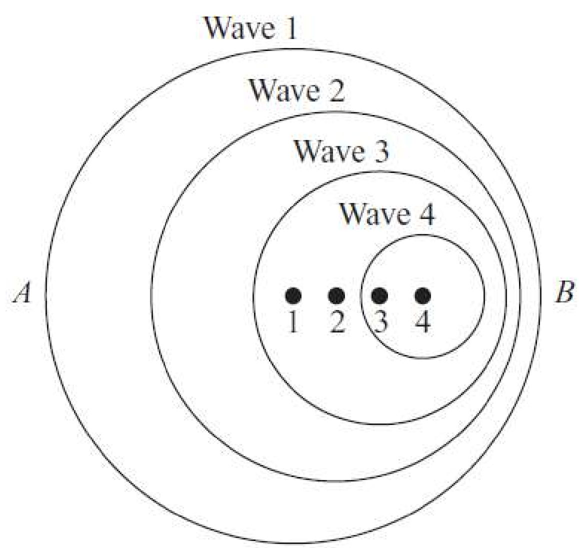
OALG 11.10.1 Observe and explain

Consider a beach ball bobbing up and down in the center of a swimming pool. Imagine that the ball remains at the same position at the center of the pool. The illustration below shows several consecutive wave crests at one instant of time. Suppose that observer *A* is moving toward the source and observer *B* is moving away from the source. Does observer *A* or *B* observe higher frequency water wave vibrations, or do they observe the same frequency vibrations? Explain.



OALG 11.10.2 Observe and explain

Four wave pulses produced by a large beach ball bobbing up and down in a pool are shown in the figure below as the ball moves to the right. Wave-crest 1 of large radius was created when the ball was at position 1, and wave-crest 4 of small radius was created when the ball was at position 4. Explain why observer *B*, standing stationary in the water in the direction the source moves, feels higher frequency water wave pulses than observer *A*, standing stationary behind the moving wave source.



OALG 11.10.3 Describe and explain

Look for a pattern in the two experiments described next.

Experiment I: You stand beside a train track; a train blowing its whistle moves toward you, passes you, and then moves away. The sound from the whistle changes from a higher pitch (higher frequency) as it moves toward you to a lower pitch as it moves away.

Experiment II: Your professor swings a ball tied to a rope in a horizontal circular path. A whistle inside the ball makes a higher-pitched sound as the ball moves toward you and a lower-pitched sound as it moves away.

Devise a qualitative explanation for these observations using the ideas you developed in Activity 11.10.2.

OALG 11.10.4 Read and interrogate

Read and interrogate Section 11.10 in the textbook and answer Review Question 11.10.

OALG 11.10.5 Reason and explain

a. We found in Activity 11.10.1 that the observed frequency is higher if the observer moves toward the stationary source and is lower if the observer moves away from the stationary source. Use Equation 11.17 in the textbook and sign conventions to show that these changes in frequency are consistent with the equation.

b. We observed and predicted in Activity 11.10.2 that the observed frequency is higher if the source moves toward the stationary observer and is lower if the source moves away from the stationary observer. Show that these changes in frequency are consistent with the equation.

OALG 11.10.6 Regular problem

The Doppler effect can be used to determine the speed of red blood cells (as well as baseballs and cars). The Doppler speed detector emits sound at a particular frequency and detects the reflected sound at a different frequency. The difference in the emitted and detected sound frequencies indicates the speed of the object being measured. Assume that sound of frequency 100,000 Hz enters an artery in the opposite direction of blood flow, which travels at speed 0.40 m/s. Answer the questions below to see how detecting the frequency of the sound reflected from a red blood cell indicates how fast it is moving.

a. Use the Doppler equation to determine the frequency that the cell would detect as it moves toward the sound source.

b. Suppose that the moving cell emits sound at the same frequency it detected in part **a**. What frequency does the Doppler detection system measure as coming from the cell?

c. Often, the Doppler detection system measures a beat frequency. The beat frequency is the magnitude of the difference between the emitted sound frequency and the reflected sound frequency that it received back from the moving blood cell. What beat frequency is observed in the case described above?