SECTION 3

Sounds in Strings Revisited

Section Overview

Students return to the vibrating strings explored in *Section 1* and interpret their results in terms of wavelength and frequency of standing wave patterns from *Section 2*. They measure the length of the vibrating string and calculate and record its wavelength. They then change the length of the vibrating string a few times to calculate the wavelength of the vibration, and make a general statement about the change in pitch as the length of the string is changed. In *Preparing for the Chapter Challenge*, students design a string instrument and are required to show how the string forms a standing wave and how its wavelength relates to the frequency and pitch that is heard.

Students also carry out an investigation with small pieces of masking tape placed at uniform intervals on the floor, covering a distance of 10 m in a straight line. They step on each piece of tape every second to calculate their total time of travel. The distance traveled divided by the time is the distance between the tape segments (students' stride length) times the number of steps per second (the frequency). By analogy, this is compared to the wave equation. Then they change their stride length (the wavelength) and frequency to explore how the relationship among wave speed, wavelength, and frequency is affected when either the wavelength or the frequency is changed.

Background Information

Wavelength and Frequency for Vibrating Strings

Students may confuse amplitude (loudness) and frequency, so they may interpret louder sounds as lower in pitch. This prior conception could hinder students from recognizing that amplitude and frequency are independent variables. To help in addressing this possible confusion, set up a frequency generator, amplifier, and speaker. Then vary the frequency and amplitude to demonstrate that all possible combinations of pitch and volume (loudness) can exist.

When the string in a musical instrument vibrates, it usually moves in a combination, or superposition, of many standing wave patterns. A guitarist can suppress certain standing waves to emphasize the remaining ones by making "chimes." The technique is to simultaneously pluck the string and lightly tap it at the right spot for the particular chime. If the guitarist taps the string right in the middle, the fundamental (the first harmonic) and all other odd harmonics with large amplitudes in the center of the string are suppressed.

Note: In this section, students find the wavelength of the fundamental (lowest pitch sound) from the length of the string. Because this section does not introduce harmonics, the wavelength is called "the wavelength of the sound."

The speed of a wave on a string depends on the material (mass per unit length), the tension in the string, and the length of the vibrating string. Students should be able to reinterpret their results from *Section 1* in terms of wavelength and frequency of standing wave patterns. As the length is made shorter, the associated wavelength is smaller and hence, the frequency is higher. Higher frequency is the physical equivalent of perceived higher pitch.

Students observed in *Section 1* that increasing the tension (for a fixed string length) increases the pitch. The frequency also increases. Because the wavelength (determined by the length of the string) stayed the same, the speed of the wave must have increased to account for the higher frequency. When the tension in the string is increased, the wave speed also increases.

Crucial Physics

- The length of a vibrating string determines the wavelength of the sound produced by the string.
- When the length of a vibrating string under constant tension is decreased, the speed of the wave on the string remains constant.
- As the wavelength of a standing wave on a string decreases, the frequency of the wave increases.
- The velocity of a wave is the product of the wave's frequency times its wavelength.
- The speed of a walking person is equal to the walker's stride length times the stride frequency.

Learning Outcomes	Location in the Section	Evidence of Understanding
Calculate the wavelength of a standing wave on a string.	***Investigate*** Steps 4 and 5	Students measure the vibrating string length and double it to obtain the wavelength and record this information in their data table.
Organize data in a table.	***Investigate*** Steps 4-8	Students record their data for string length, wavelength and pitch in a data table.
Describe how the pitch of the sound produced by a vibrating string depends on the wave speed, wavelength, and frequency of the waves on the string.	***Investigate*** Steps 7 and 8	Students record a general statement of how pitch and string length relate to one another.

Section 3 Materials, Preparation, and Safety

Materials and Equipment

PLAN A		
Materials and Equipment	**Group (4 students)**	**Class**
Meter sticks	1 per group	
3″ C-clamp	1 per group	
500-g weight with hook	4 per group	
Pulley with mount	1 per group	
Safety glasses, impact	4 per group	
Styrene-foam cup, 12 ounces	2 per group	
Scissors	1 per group	
Fishing line - 30 lb. test (55 yards)	1 per group	

*Additional items needed not supplied

Time Requirement

- Allow 30 minutes for students to complete the *Investigate* part of this section.

Teacher Preparation

- Test the string prior to students completing the *Investigate* to ensure that the string is capable of handling the required tension with a safety margin of a factor of two.
- Assemble the required material and set up the experiment in advance to find out how long the string must be.
- Use nylon monofilament rated at least 15-lb test. Cut the string in advance, and be sure the string is long enough to drape over the pulley and be tied to the mass hanger.

Safety Requirements

- Students must wear safety goggles for this *Investigate*.
- The masses attached to the string that hang over the pulley may fall to the floor if the string breaks or if dislodged. Make certain students do not have their feet underneath the masses. Placing a soft pad on the floor beneath the masses will prevent damage to the floor if the masses fall.
- If monofilament line is used, be aware that this line may be difficult to tie to a mass or mass hanger. Students should knot the line several times for safety.

NOTES

Materials and Equipment

PLAN B		
Materials and Equipment	**Group (4 students)**	**Class**
Meter sticks		1 per class
3″ C-clamp		1 per class
500-g weight with hook		4 per class
Pulley with mount		1 per class
Safety glasses, impact		4 per class
Styrene-foam cup, 12 ounces		1 per class
Scissors		1 per class
Fishing line - 30 lb. test (55 yards)		1 per class

*Additional items needed not supplied

Time Requirement

- Allow one class period or 45 minutes to complete the *Investigate* as a whole-class demonstration, discuss the *Physics Talk* as well as complete the other portions of the section as outlined in the *Pacing Guide*.

Teacher Preparation

- Note the teacher preparation items in *Plan A*.
- Prepare a transparency of a sample data table for the students to record in their logs, and to record the data taken during the *Investigate*. A student volunteer recording the data on transparency on an overhead projector is suggested.

Safety Requirements

- Wear safety goggles for this *Investigate*.
- Be aware that the masses attached to the string that hang over the pulley may fall to the floor if the string breaks or if dislodged. Placing a soft pad on the floor beneath the masses will prevent damage to the floor if the masses fall.
- If monofilament line is used, be aware that this line may be difficult to tie to a mass or mass hanger. Knot the line several times for safety.

CHAPTER 5

NOTES

Meeting the Needs of All Students

Differentiated Instruction: Augmentation and Accommodations

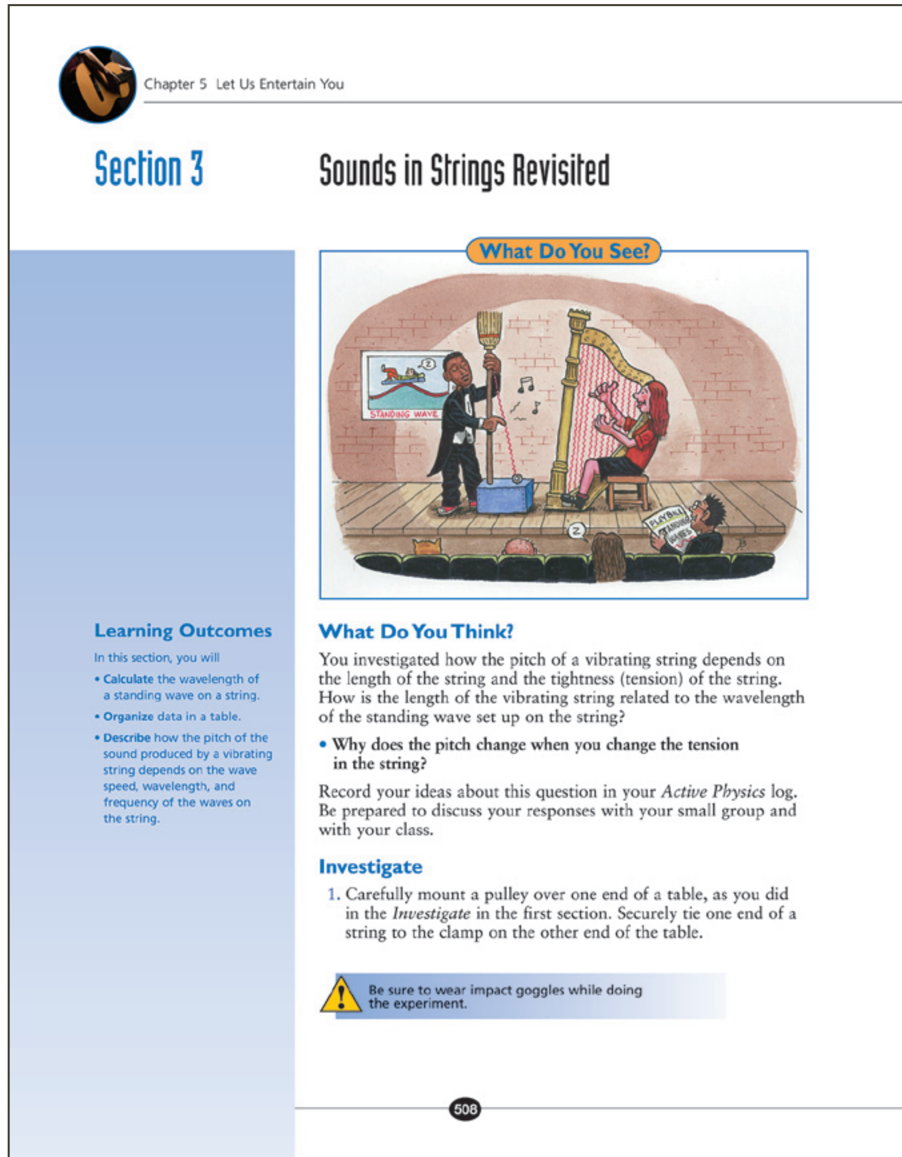
Learning Issue	Reference	Augmentation and Accommodations
Constructing a data table without a model	***Investigate*** Step 4.a)	**Augmentation** • Students should be gaining some independence in creating data tables by this point in the text; however, students with fine motor and executive-function issues may still be struggling to create tables without a model. Instruct students to turn their page to landscape format and draw two vertical lines to divide the page into three equal columns. Next, instruct students to draw four horizontal lines that divide the page into five equal rows. Students can then create the outside boundaries for their table by boxing in the columns and rows they have created. Make sure students label the columns in the first row of their tables (length of string, wavelength, and frequency). • The instructions above will be more effective if they are paired with a visual model. Either draw the table as the instructions are given, or provide a completed model for students to view. **Accommodation** • Provide a blank table for students to complete as they collect their data.
Understanding relationships between variables without using numbers	***Physics Talk*** ***Checking Up*** Question 1	**Augmentation** • Students struggle to understand, compare, and manipulate fractions that contain numbers in the numerator and denominator. Therefore, asking students to understand the inverse and direct relationships between frequency, wavelength, and wave speed with variables is very challenging. • Show students a few examples with values for v, f, and λ. For example, if $v = 1$ m/s and $\lambda = 4$ m, the frequency is $\frac{1}{4}$. Then if $v = 1$ m/s and $\lambda = 2$ m, the frequency is $\frac{1}{2}$. The value in the denominator (λ) has decreased, and the value for (f) has increased. Students will have an easier time comparing 0.25 and 0.50 because they are familiar with these common decimals and can relate them to monetary values. • Show students the relationship using arrows or hand gestures. If one value increases, the other increases and vice versa. If $\lambda\uparrow$, then $f\downarrow$. If $v\uparrow$, then $f\uparrow$. • Make an explicit connection between the “stepping” investigation and these relationships. Ask students to repeat the investigation if they are struggling to understand the relationships.
Reading comprehension	***Physics Talk*** ***Physics to Go*** Questions 1-7	**Augmentation** • Students are asked to read a series of paragraphs that are laden with physics vocabulary and explanations of mathematical relationships. This task may be difficult for students who struggle with reading and/or understanding math concepts. • Ask students to read the *Physics to Go* questions before they read the *Physics Talk* section. The questions will provide a purpose for their reading. • Assist students in creating a graphic organizer that shows the relationships amongst length, tension, frequency, wavelength, and wave speed more visually while using fewer words. **Accommodation** • Provide a copy of the text to allow students to highlight answers as they are reading. • Provide a copy of the questions to allow students to easily look back and forth between the questions and the text.

Strategies for Students with Limited English-Language Proficiency

Learning Issue	Reference	Augmentation
Vocabulary comprehension	***Investigate*** Step 3	Students learned about standing waves in the preceding section, but the term is more explicitly defined here. Be sure they understand that a "standing wave" is a wave that vibrates back and forth between two fixed (unmoving) "endpoints." The two endpoints are "nodes," and at the center of the vibrating string is the "antinode," the point at which the vibrating string has the greatest "displacement." To fully comprehend the concepts discussed in this section, students must understand standing waves. It may be a good idea to have students draw and label a standing wave in their *Active Physics* log, and write the definitions of standing wave, endpoints, node, antinode, and displacement as well. Review the logs and correct any misunderstandings before moving on.
Vocabulary comprehension Understanding concepts	***Physics Talk***	After students have encountered the terms "inverse relationship" and "direct relationship," have them look back at the general statements they made in *Step 7* of the *Investigate* and identify each relationship as an inverse relationship, where one variable decreases as the other increases, or a direct relationship, where both variables either increase or decrease together.
Using equations Understanding concepts	***Physics Talk***	There are several mathematical equations in this section. As your students work through them, have them think about inverse relationships and direct relationships, and relate in words the relationships expressed by each equation. Have them write each equation and its written explanation in their *Active Physics* logs for your review.
Vocabulary comprehension	***Physics Talk*** Sample Problem 1	Be sure students understand the "period" of a wave: the amount of time for one vibration. To help clarify the meaning, remind students of the definition used in the preceding section: the time it takes to complete one cycle of the wave, or the time required for a full cycle (crest-trough-crest) to pass a given point. It is crucial that students do not confuse period with "frequency": the number of vibrations per second. Frequency is the reciprocal of the period. Students will also need help understanding the term "reciprocal." Tell them that reciprocals come in pairs. Reciprocals are two numbers that when multiplied together equal 1. You determine the reciprocal of a number by inverting the number written as a fraction. For example, the reciprocal of 5 (which can be written as $5/1$) is $1/5$; the reciprocal of $1/7$ is $7/1$, or 7.

SECTION 3

Teaching Suggestions and Sample Answers


Chapter 5 Let Us Entertain You

Section 3 Sounds in Strings Revisited

What Do You See?

Learning Outcomes

In this section, you will

- **Calculate** the wavelength of a standing wave on a string.
- **Organize** data in a table.
- **Describe** how the pitch of the sound produced by a vibrating string depends on the wave speed, wavelength, and frequency of the waves on the string.

What Do You Think?

You investigated how the pitch of a vibrating string depends on the length of the string and the tightness (tension) of the string. How is the length of the vibrating string related to the wavelength of the standing wave set up on the string?

- Why does the pitch change when you change the tension in the string?

Record your ideas about this question in your *Active Physics* log. Be prepared to discuss your responses with your small group and with your class.

Investigate

1. Carefully mount a pulley over one end of a table, as you did in the *Investigate* in the first section. Securely tie one end of a string to the clamp on the other end of the table.

Be sure to wear impact goggles while doing the experiment.

508

What Do You See?

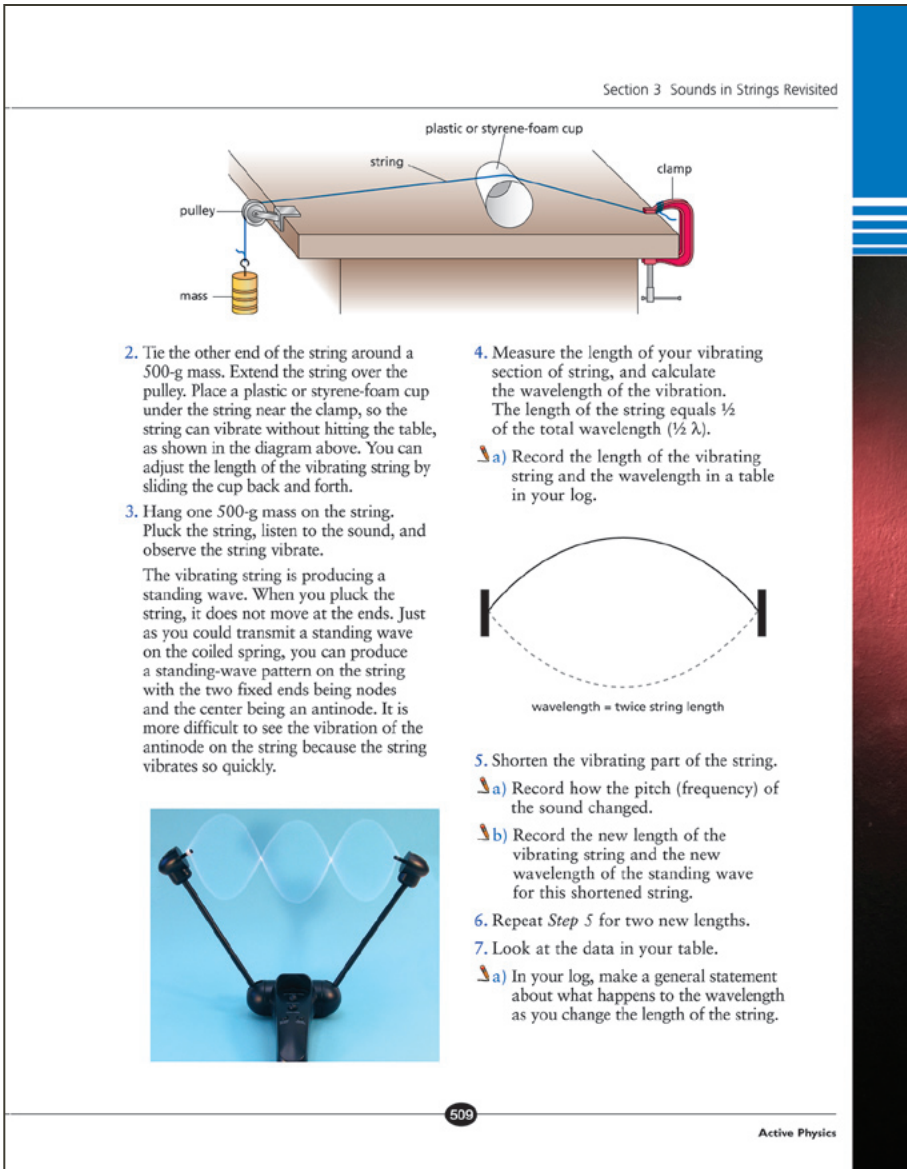
Ask students to study the *What Do You See?* illustration. They might comment on the homemade instrument that resembles a "washboard bass" or the musician playing the harp. They might comment on the person resting on a standing wave in the poster on the wall or the person sitting in the audience holding a program that mentions the evening's performance of "Standing Waves." Listen to your students' responses and encourage them to relate the illustration to what they already know about sounds produced by strings. Encourage them to look for clues in the illustration that reveal the properties of standing waves.

What Do You Think?

Students will come up with a range of answers. Students might know how the length of the vibrating string is related to the wavelength of the standing wave. Encourage them to discuss and share their ideas. Accept all answers because at this stage, the validity of their answers does not matter. This is simply a chance to gauge students' prior conceptions and provides you with an opportunity to link their

Students' Prior Conceptions

This section presents the opportunity for you to revisit and listen to student conversations and explanations. Both you and the student, through model-building, processing *Inputs* in the *Engineering Design Cycle*, and receiving *Feedback* on these processes may determine students' prior conceptions. Review students' predictions and outcomes in the first three sections, as it sets the stage for deeper understanding and cognitive development of those scientific ideas presented in subsequent sections. You should pay close attention to student models explaining pitch, amplitude, frequency, and wavelength. Students should make predictions on the similarities and differences in the nature of wavelength and frequency for sounds from various sources that have the same and different frequencies.



2. Tie the other end of the string around a 500-g mass. Extend the string over the pulley. Place a plastic or styrene-foam cup under the string near the clamp, so the string can vibrate without hitting the table, as shown in the diagram above. You can adjust the length of the vibrating string by sliding the cup back and forth.

3. Hang one 500-g mass on the string. Pluck the string, listen to the sound, and observe the string vibrate.

The vibrating string is producing a standing wave. When you pluck the string, it does not move at the ends. Just as you could transmit a standing wave on the coiled spring, you can produce a standing-wave pattern on the string with the two fixed ends being nodes and the center being an antinode. It is more difficult to see the vibration of the antinode on the string because the string vibrates so quickly.

4. Measure the length of your vibrating section of string, and calculate the wavelength of the vibration. The length of the string equals ½ of the total wavelength (½ λ).

a) Record the length of the vibrating string and the wavelength in a table in your log.

5. Shorten the vibrating part of the string.

a) Record how the pitch (frequency) of the sound changed.

b) Record the new length of the vibrating string and the new wavelength of the standing wave for this shortened string.

6. Repeat *Step 5* for two new lengths.

7. Look at the data in your table.

a) In your log, make a general statement about what happens to the wavelength as you change the length of the string.

509 Active Physics

understanding from what they already know to what they will be learning when they carry out the investigation in this section. Remind students that they will be returning to their responses later in the *What Do You Think Now?* section.

What Do You Think?

A Physicist's Response

When the string is displaced from its position of rest, the forces between adjacent molecules try to pull the displaced part of the string back toward its original position. Increasing the tension in the string increases the forces between the molecules in the string. This increased force leads to an increased acceleration of the mass of the string (which does not change), resulting in a higher velocity and vibration rate. The pitch, therefore, increases when the tension in the string increases.

Investigate

1.-3.

Students set up the equipment for the investigation.

4.

Students will measure the length of the vibrating section of the string, and calculate the wavelength of the vibration. They should construct a data table that will have string length, wavelength, and pitch for each column.

4.a)

Students record the string length between the clamped end and the cup, and then the wavelength (twice the recorded string length). For the lowest frequency standing wave, (antinode in the middle, nodes only at the ends), the wavelength is twice the length of the vibrating string. Students should be encouraged to look at their results from standing waves on a spring.

5.a)

Students should observe that the pitch (frequency) increases as the string is made shorter. The tension stays the same.

5.b)

Students record their data for the changing string length and pitch. The string lengths should differ by at least 30-50 percent to make the changes more obvious.

6.

Students repeat the measurements for shorter strings.

7.a)

Students should recognize that the wavelength decreases when the length of the vibrating part of the string decreases.

7.b)

Students should recognize that the wave frequency increases as the length of the vibrating part of the string decreases. All of this assumes that the tension in the string remains fixed.

8.a)

The wave property that changes when the tension is increased is the wave speed on the string. Because the wavelength does not change, the faster the wave travels, the greater the frequency of the wave, and the higher the pitch.

9.a)

Students record their data to calculate the speed. They use speed equals distance divided by time, and then compare it to the wave equation of speed equals frequency times wavelength. This investigation illustrates the relationship between wave speed (how fast the walker is moving), the wavelength (distance between pieces of tape), and the wave frequency (the number of steps per unit time).

10.a)

Students should again find that the product of frequency (1 step per second) and wavelength (60 cm) is equal to their speed found by dividing the distance traveled by the elapsed time.

11.a)

Students should find that the product of frequency ($\frac{1}{2}$ step per second) and wavelength (60 cm) is equal to their speed found by dividing the distance traveled by the elapsed time.

b) Make a second general statement about what happens to the pitch or frequency of the sound as you change the length of the string.

8. In the first section, you changed the tension in the string by adding weights and observed a change in pitch—the greater the tension, the higher the pitch. Since the length of the string stayed the same, the wavelength must have also stayed the same.

a) What wave property changed to make the frequency higher? (Hint: Recall the wave equation, $v = f\lambda$. If the wavelength remains the same and the frequency changes, what else needs to change?)

9. You can explore the relationship among wave speed, wavelength, and wave frequency with the following investigation. You may have to do this investigation in the hall or outside on the sidewalk or athletic field.

Place small pieces of masking tape about 30 cm apart on the floor. Cover a distance of about 10 m in a straight line. Now walk, stepping on each piece of tape by taking one step each second. Your "frequency" is one step per second and your "wavelength" is 30 cm (the distance between pieces of tape).

To help you perform this task, have a member of your group call out the time using a stopwatch.

a) Time your overall travel and then calculate your speed by dividing the total distance traveled by the time elapsed. Compare that result to what you find from multiplying wavelength times frequency.

10. Now change your "wavelength" by stepping on every other piece of tape. Keep the same frequency (one step per second).

a) Again, compare your speed for the trip with the result obtained by multiplying wavelength by frequency.

11. Now change your frequency by taking one step every two seconds. Make your wavelength 30 cm.

a) Again, compare your speed for the trip with the result of multiplying wavelength by frequency.

12. Make up your own combination of frequency and wavelength and see how they affect your speed.

a) Record your findings in your *Active Physics* log.

Physics Talk

WAVELENGTH, WAVE SPEED, AND FREQUENCY

Frequency and Wavelength

The vibrating string producing the sound is actually setting up a standing wave between its endpoints. The length of the string determines the wavelength of this standing wave. If the string is 40 cm, then the wavelength of the lowest-frequency standing wave is 80 cm. The length of the string is always ½ the wavelength of the lowest-frequency standing wave.

The pitch that you hear is related to the frequency of the wave. The higher the pitch, the higher the frequency. You expressed this with a mathematical equation.

12.a)

Students should again find that the product of frequency and wavelength is equal to their speed found by dividing the distance traveled by the elapsed time.

Physics Talk

The relationship between wavelength, frequency, and speed is discussed in this section. Observations made in the *Investigate* are explained in detail, so that students know how the string length and wave speed determine the pitch of standing waves. Point out to students that the length of a string is always half the wavelength of its lowest frequency wave. Consider giving them an arbitrary length of a string and ask them what the frequency for the standing wave of that string would be. As students recall the wave equation, To get a higher frequency, you have to shorten the string or generate a smaller wavelength. Recall the wave equation:

Wave speed = wave frequency × wavelength

In symbolic form,

$$v = f\lambda$$

where v = speed,
f = frequency, and
λ = wavelength.

You can rewrite this equation to solve for frequency. Divide both sides of the equation by the wavelength:

$$f = \frac{v}{\lambda}$$

Now analyze the equation and ensure that it is consistent with your experimental findings in the *Investigate*. When you shortened the length of the string, you also shortened the wavelength of the standing wave. You found that this shorter wavelength increased the pitch. An increase in pitch corresponds to an increase in frequency. When you shortened the wavelength of the string's standing wave, you increased the frequency.

The equation above shows this as well. When the wavelength gets shorter, the denominator on the right side of the equation gets smaller. When the denominator gets smaller, the value of the fraction gets larger (as long as the numerator stays the same). For example, $\frac{1}{100}$ is much smaller than $\frac{1}{2}$. If the fraction on the right side of the equation gets larger, then the left side of the equation also gets larger. In the equation, $f = \frac{v}{\lambda}$, the frequency gets larger.

This is what your experiment demonstrated. The shorter the wavelength is, the higher the frequency. This is called an **inverse relationship.** In an inverse relationship, decreasing one variable increases the other variable or vice versa. In this instance, decreasing the wavelength increases the frequency and pitch.

decreasing the wavelength increases the frequency and pitch

Physics Words

inverse relationship: a relationship in which decreasing one variable increases the other variable or vice versa.

Tension and Thickness of a String and Frequency

How are tension and pitch related? In the first section of this chapter, you also found that changing the tension in the string by adding masses would change the frequency or pitch of the sound. When you increased the tension, you did not change the wavelength of the standing wave.

You can use the equation $f = \frac{v}{\lambda}$ to help you understand what happened.

Since the wavelength did not change, and the frequency increased, you must conclude that the speed of the wave increased.

have them share their analysis of the equation with the whole class. You might want to ask them how the *Investigate* demonstrates that decreasing the wavelength increases the frequency and pitch.

Draw students' attention to how the tension in the string relates to the frequency of the sound produced. Discuss how a larger tension produces a greater accelerating force on the string, and thus, a greater vibration rate. Point out that since the wavelength has not changed, the wave speed must have increased. To check if students have grasped how tension and wave speed are related, have them explain in their logs why disturbances travel faster if the tension in a string is increased. Prompt students to discuss tension and wave speed by highlighting the direct relationship between these two variables. At the same time, students should be able to explain the inverse relationship between the thickness of a string and the wave speed. Ask what effect the increased mass of the string has on the lateral acceleration of the string, and hence, its vibration rate.

This *Physics Talk* provides an opportunity to reinforce algebra instruction through sample problems. Emphasize that as students are studying these problems that each equation highlights the relationship among variables that affect the motion of a wave. Prompt students to point out the direct and inverse relationship between variables in each sample problem.

The increased tension in the string means that a portion of the string that is displaced to the side will feel a larger force pulling it back toward its rest position. An increase in tension produces a larger force. A larger force will produce a greater acceleration on that portion of the string that is displaced and make it vibrate faster. This vibration makes the disturbance travel more quickly down the string.

In the equation, $f = \frac{v}{\lambda}$, increasing the wave speed increases the value of the right side of the equation. This corresponds to an increase of the left side of the equation or an increase in frequency. This a **direct relationship.** Increasing one variable also increases the other variable. In this case, the wave speed increases and therefore the frequency or pitch must increase.

Physics Words

direct relationship: a relationship in which increasing one variable increases the other variable or decreasing one variable also decreases the other variable.

increasing the wave speed increases the frequency and pitch

How does increasing the thickness of the string lead to a different wave speed in the string? You know from looking at guitars or violins or the inside of pianos that the thick strings produce the lower frequency sounds. The increased mass in the string means that a portion of the string that is displaced to the side will require an increased force to pull it back toward its rest position. This force is the tension produced in the string. For a given amount of tension force, a heavier mass will have a smaller acceleration on the displaced portion of the string and hence, it will move more slowly back and forth. The decrease in acceleration will make the disturbance travel more slowly down the string.

Because the tension changes the wave speed, a weaker tension would mean a wave travels more slowly on the spring.

In the equation, $f = \frac{v}{\lambda}$, decreasing the wave speed decreases the value of the right side of the equation. This corresponds to a decrease of the left side of the equation or a decrease in frequency.

Is There an Equation?

Standing waves occur when the length of the coiled spring or string and the wavelength have a particular relationship. The length of the coiled spring must equal ½ wavelength, 1 wavelength, $\frac{3}{2}$ wavelengths, 2 wavelengths, and so on. Mathematically, this can be stated as

$$L = \frac{n\lambda}{2}$$

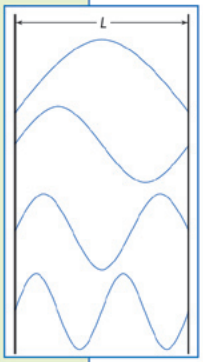
Section 3 Sounds in Strings Revisited

where L is the length of the coiled spring,

λ is the wavelength, and

n is a number (1, 2, 3…).

The number n is the number of antinodes in the standing wave pattern.



Sample Problem I

You and your partner sit on the floor and stretch out a coiled spring to a length of 3.5 m. You shake the coiled spring so that the pattern has one antinode between the two of you. Your partner measures the time for 10 vibrations and finds that it takes 24.0 s for the coiled spring to make 10 vibrations.

a) What is the wavelength of this wave?

Strategy: Draw a sketch of the wave you made. It should look like the first wave pattern in the diagram. It is one-half of a full cycle of the wave. This is the maximum wavelength for a standing wave on this length of coiled spring. You can use the equation that shows the relationship between the length of the coiled spring and the wavelength.

Given:

$L = 3.5$ m

$n = 1$

Solution:

$$L = \frac{n\lambda}{2}$$

Rearrange the equation to solve for λ.

$$\lambda = \frac{2L}{n} = \frac{2(3.5\text{ m})}{1} = 7.0\text{ m}$$

Notice that the wavelength is twice the length of the coiled spring.

b) What is the period of vibration of the wave?

Strategy: The period is the amount of time for one vibration. You have the amount of time for 10 vibrations.

Solution:

$$T = \frac{\text{time for 10 vibrations}}{\text{10 vibrations}} = \frac{24.0\text{ s}}{10} = 2.4\text{ s}$$

CHAPTER 5

Checking Up

1.

If you decrease the wavelength of a wave, the frequency increases. This can be expressed in the following equation:

$f = v/\lambda$ where v = wave speed, f = wave frequency, and λ = wavelength.

2.

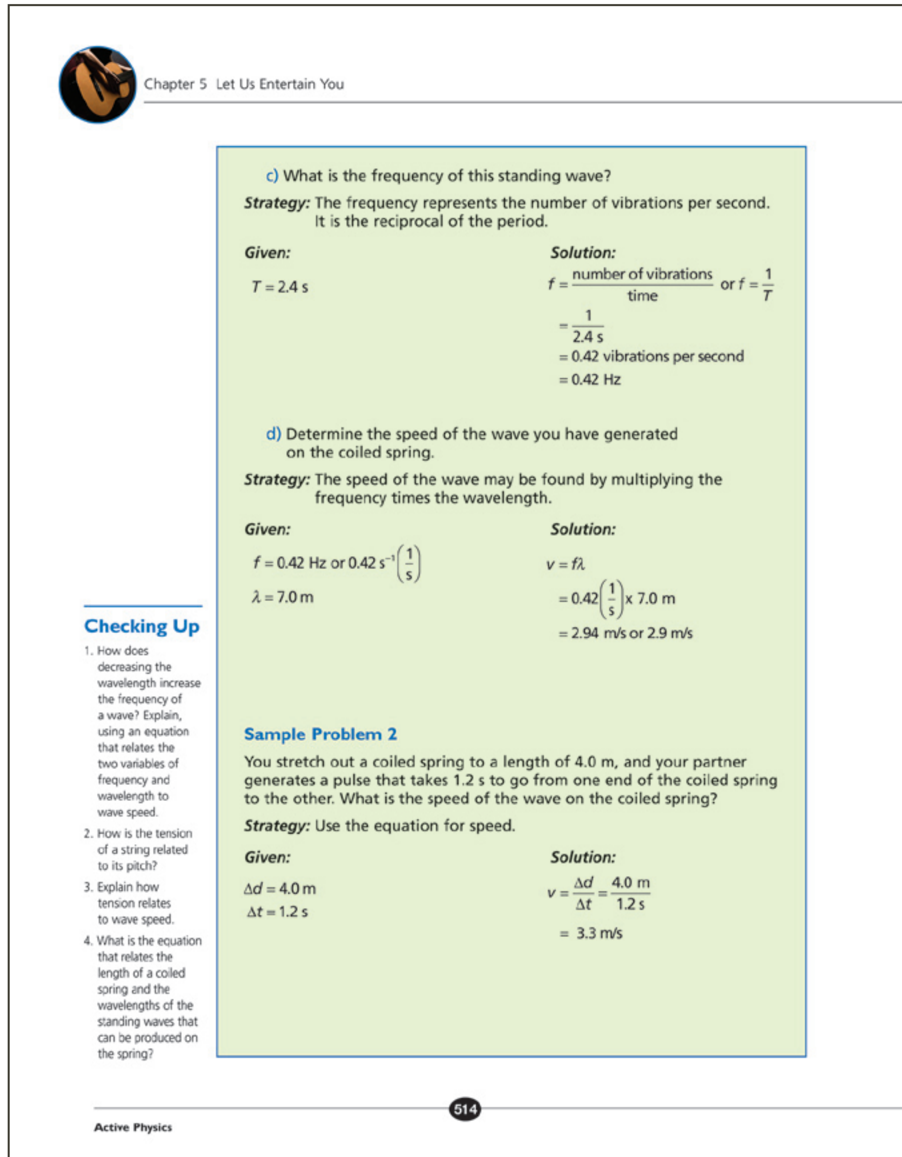
Increasing the tension of the string increases its pitch.

3.

When the tension in the string is increased, the wave speed increases. The speed of a wave is directly related to the restoring force or tension because a stronger force will produce a greater acceleration on that portion of the string that is displaced.

4.

The equation that relates the length of a coiled spring and the wavelengths of the standing waves that can be produced on the spring is $L = n\lambda/2$.



Chapter 5 Let Us Entertain You

c) What is the frequency of this standing wave?

Strategy: The frequency represents the number of vibrations per second. It is the reciprocal of the period.

Given:

$T = 2.4\text{ s}$

Solution:

$f = \dfrac{\text{number of vibrations}}{\text{time}}$ or $f = \dfrac{1}{T}$

$= \dfrac{1}{2.4\text{ s}}$

$= 0.42$ vibrations per second

$= 0.42\text{ Hz}$

d) Determine the speed of the wave you have generated on the coiled spring.

Strategy: The speed of the wave may be found by multiplying the frequency times the wavelength.

Given:

$f = 0.42\text{ Hz or } 0.42\text{ s}^{-1}\left(\dfrac{1}{\text{s}}\right)$

$\lambda = 7.0\text{ m}$

Solution:

$v = f\lambda$

$= 0.42\left(\dfrac{1}{\text{s}}\right) \times 7.0\text{ m}$

$= 2.94\text{ m/s or } 2.9\text{ m/s}$

Sample Problem 2

You stretch out a coiled spring to a length of 4.0 m, and your partner generates a pulse that takes 1.2 s to go from one end of the coiled spring to the other. What is the speed of the wave on the coiled spring?

Strategy: Use the equation for speed.

Given:

$\Delta d = 4.0\text{ m}$

$\Delta t = 1.2\text{ s}$

Solution:

$v = \dfrac{\Delta d}{\Delta t} = \dfrac{4.0\text{ m}}{1.2\text{ s}}$

$= 3.3\text{ m/s}$

Checking Up

1. How does decreasing the wavelength increase the frequency of a wave? Explain, using an equation that relates the two variables of frequency and wavelength to wave speed.
2. How is the tension of a string related to its pitch?
3. Explain how tension relates to wave speed.
4. What is the equation that relates the length of a coiled spring and the wavelengths of the standing waves that can be produced on the spring?

514

Active Physics

Section 3 Sounds in Strings Revisited

Active Physics **Plus**

+Math	+Depth	+Concepts	+Exploration
••			

Is There an Equation?

A vibrating string sets up a standing wave. The frequency of the sound can be increased by shortening the string length, by increasing the tension, or by using a thinner string (thereby decreasing the mass). You can derive an equation that combines all of these relationships.

$$f = \frac{v}{\lambda}$$

Since the wavelength is ½ the length of the string: $\lambda = 2L$

$$f = \frac{v}{2L}$$

From other studies, physicists have found

$$v = \sqrt{\frac{T}{m/L}}$$

where m = mass of one string,
L = length of the string, and
T = tension of the string.

By combining these equations:

$$f = \frac{\sqrt{\frac{T}{m/L}}}{2L} = \sqrt{\frac{T}{4mL}}$$

1. A standard acoustic guitar has six strings. For the highest pitch notes, a thin string is used. For the lowest notes, a thick string is used. For the intermediate pitch notes, a medium thickness string is used. The string tension is controlled by the tuning pegs at the end of the guitar. To keep the neck of the guitar from bending to one side or the other, you want to have the tension in all of the strings about the same. Using what you learned in this section, explain why the guitar designer decided to use thick strings for the low notes and thin strings for the high notes.

What Do You Think Now?

At the beginning of this section you were asked the following:

- **Why does the pitch change when you change the tension in the string?**

Use what you learned in this section to explain how the length of a vibrating string is related to the wavelength of a standing wave on the string, how the pitch of a vibrating string changes when you change the tension of the string, and how the thickness of the string affects the velocity and the frequency of a standing wave on a string.

515

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By studying the wave equation in terms of the tension, mass, and length of the string, students learn that strings with the same length vibrate when plucked while under tension. Tension is the force that tends to pull the string back to its equilibrium position. A light string (less mass per unit length) will vibrate at a higher frequency than a heavy string (more mass per unit length) when under the same tension. Therefore, thick strings (higher mass per unit length) will have a lower wave speed for a given tension than thin strings (lower mass per unit length). By using strings of different thickness (mass per unit length) the guitar designer can have all the strings at almost the same tension, yet still have the strings vibrate at different frequencies, and thus, produce the different notes needed to play the music.

1.

If the string has more mass per unit length (a thicker or heavier string), the acceleration of a displaced piece of the string will be smaller and the time to move back toward the equilibrium position will be longer; hence, its vibration frequency (oscillations per second) will be lower. The guitar designer decided to use thick strings for the low notes and thin strings for the high notes because for a given string length and more or less the same tension, a thick string will produce a lower pitch note than a thinner string.

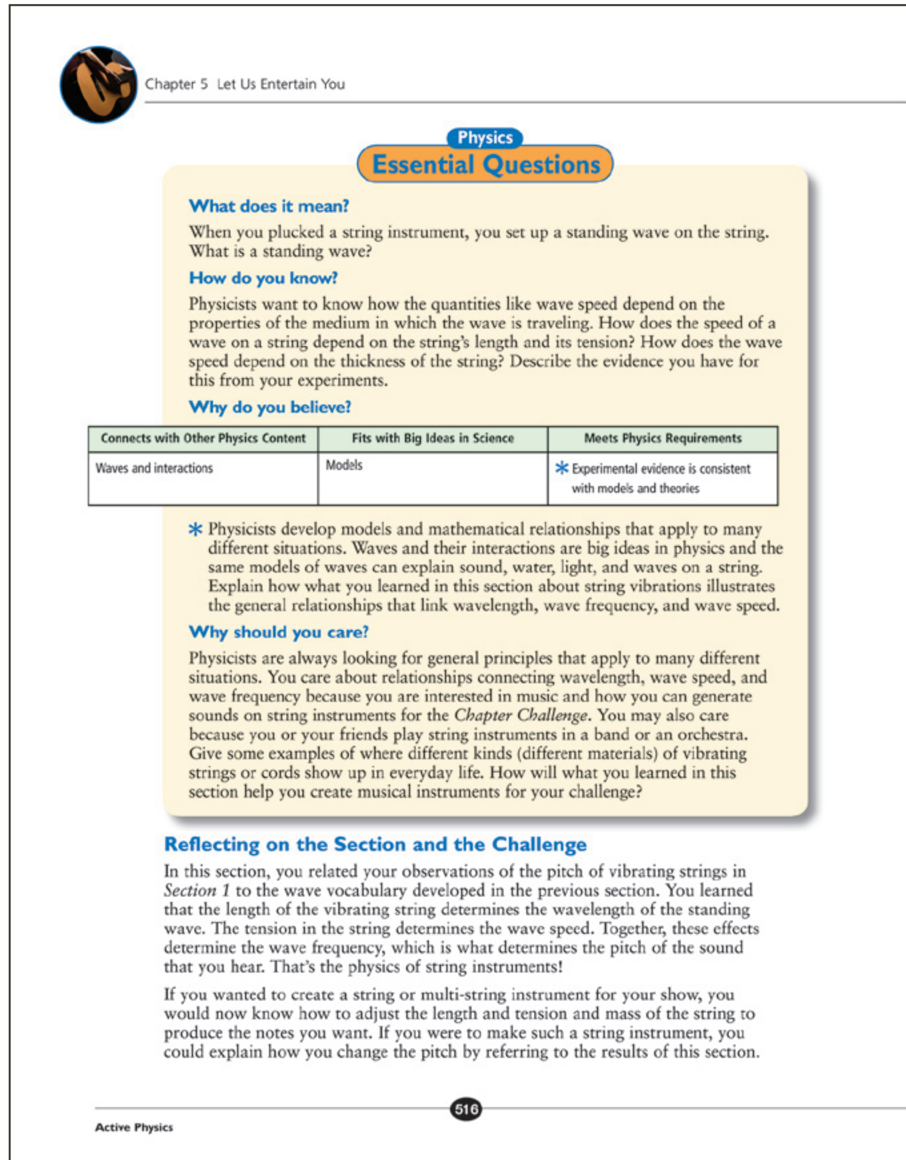
What Do You Think Now?

Ask students to revisit their original response to the *What Do You Think?* question and have them update their response to reflect on what they have learned so far in this section. Consider sharing *A Physicist's Response* to give them further opportunity to ponder the relationship between the tension in a string and the pitch of the sound it produces.

CHAPTER 5

Reflecting on the Section and the Challenge

Allow students to reflect on the physics of string instruments. Ask them to write down in their logs how each concept studied so far in all the three sections relates to wave motion. Remind them that this is their opportunity to start thinking of the instruments they will be using for their sound and light show. Students should ponder the effects of changing string length and string thickness when they are designing their own instruments. Encourage them to make a list of what they will need for their show and what they already have in order to produce a successful *Chapter Challenge*.



Chapter 5 Let Us Entertain You

Physics **Essential Questions**

What does it mean?

When you plucked a string instrument, you set up a standing wave on the string. What is a standing wave?

How do you know?

Physicists want to know how the quantities like wave speed depend on the properties of the medium in which the wave is traveling. How does the speed of a wave on a string depend on the string's length and its tension? How does the wave speed depend on the thickness of the string? Describe the evidence you have for this from your experiments.

Why do you believe?

Connects with Other Physics Content	Fits with Big Ideas in Science	Meets Physics Requirements
Waves and interactions	Models	* Experimental evidence is consistent with models and theories

* Physicists develop models and mathematical relationships that apply to many different situations. Waves and their interactions are big ideas in physics and the same models of waves can explain sound, water, light, and waves on a string. Explain how what you learned in this section about string vibrations illustrates the general relationships that link wavelength, wave frequency, and wave speed.

Why should you care?

Physicists are always looking for general principles that apply to many different situations. You care about relationships connecting wavelength, wave speed, and wave frequency because you are interested in music and how you can generate sounds on string instruments for the *Chapter Challenge*. You may also care because you or your friends play string instruments in a band or an orchestra. Give some examples of where different kinds (different materials) of vibrating strings or cords show up in everyday life. How will what you learned in this section help you create musical instruments for your challenge?

Reflecting on the Section and the Challenge

In this section, you related your observations of the pitch of vibrating strings in *Section 1* to the wave vocabulary developed in the previous section. You learned that the length of the vibrating string determines the wavelength of the standing wave. The tension in the string determines the wave speed. Together, these effects determine the wave frequency, which is what determines the pitch of the sound that you hear. That's the physics of string instruments!

If you wanted to create a string or multi-string instrument for your show, you would now know how to adjust the length and tension and mass of the string to produce the notes you want. If you were to make such a string instrument, you could explain how you change the pitch by referring to the results of this section.

516

Active Physics

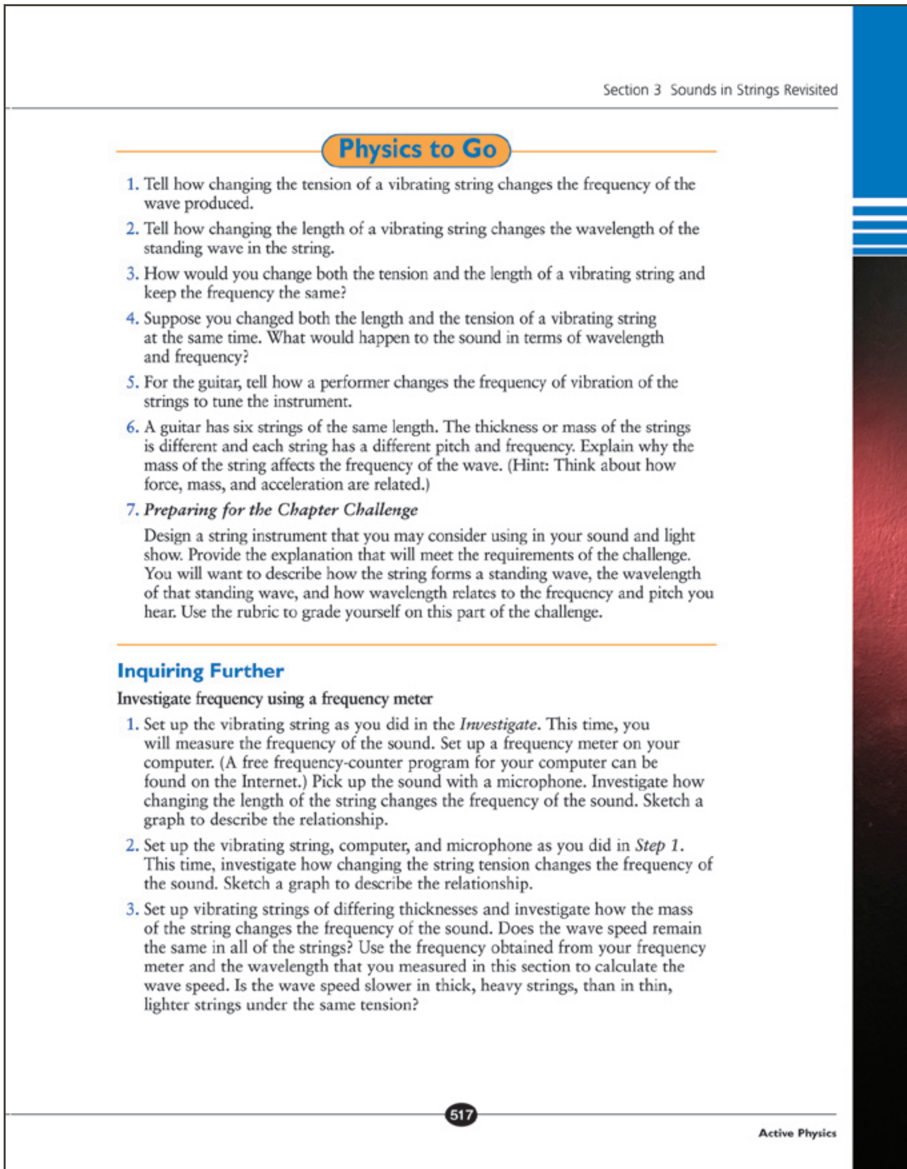
Physics Essential Questions

What does it mean?

A standing wave is the sum of two waves traveling in opposite directions.

How do you know?

The standing wave is set up along the string. The string's length determines the wavelength of the standing wave, since the two ends of the standing wave must be nodes. The vibration of the wave determines its frequency (pitch). From the wavelength and frequency, the velocity ($v = f\lambda$) can be determined. Changing the length of the string changes the wavelength and the frequency of the wave. A larger wavelength results in a lower frequency. Changing the tension in the string changes the velocity and the frequency of the wave (the wavelength of the wave remains constant). A larger tension results in a higher speed and a higher frequency. Changing the thickness of the string changes the inertia and decreases the wave velocity and frequency. These statements are supported by experiments that varied the string length and string tension.



Physics to Go

1. Tell how changing the tension of a vibrating string changes the frequency of the wave produced.
2. Tell how changing the length of a vibrating string changes the wavelength of the standing wave in the string.
3. How would you change both the tension and the length of a vibrating string and keep the frequency the same?
4. Suppose you changed both the length and the tension of a vibrating string at the same time. What would happen to the sound in terms of wavelength and frequency?
5. For the guitar, tell how a performer changes the frequency of vibration of the strings to tune the instrument.
6. A guitar has six strings of the same length. The thickness or mass of the strings is different and each string has a different pitch and frequency. Explain why the mass of the string affects the frequency of the wave. (Hint: Think about how force, mass, and acceleration are related.)
7. ***Preparing for the Chapter Challenge***

   Design a string instrument that you may consider using in your sound and light show. Provide the explanation that will meet the requirements of the challenge. You will want to describe how the string forms a standing wave, the wavelength of that standing wave, and how wavelength relates to the frequency and pitch you hear. Use the rubric to grade yourself on this part of the challenge.

Inquiring Further

Investigate frequency using a frequency meter

1. Set up the vibrating string as you did in the *Investigate*. This time, you will measure the frequency of the sound. Set up a frequency meter on your computer. (A free frequency-counter program for your computer can be found on the Internet.) Pick up the sound with a microphone. Investigate how changing the length of the string changes the frequency of the sound. Sketch a graph to describe the relationship.
2. Set up the vibrating string, computer, and microphone as you did in *Step 1*. This time, investigate how changing the string tension changes the frequency of the sound. Sketch a graph to describe the relationship.
3. Set up vibrating strings of differing thicknesses and investigate how the mass of the string changes the frequency of the sound. Does the wave speed remain the same in all of the strings? Use the frequency obtained from your frequency meter and the wavelength that you measured in this section to calculate the wave speed. Is the wave speed slower in thick, heavy strings, than in thin, lighter strings under the same tension?

Physics to Go

1.

Increasing the tension of the string increases the frequency of the vibrating string.

2.

Increasing the length of the vibrating string increases the wavelength of the standing wave pattern.

3.

Either increasing both the length and tension or decreasing both the length and tension would keep the frequency the same.

4.

The wavelength and frequency would both change if the length increased and the tension decreased or vice versa. If both the length and the tension increased or decreased together, the degree of change will determine the change in pitch.

CHAPTER 5

Why do you believe?

In all stringed instruments, standing waves are created along the length of the string. These standing waves determine the wavelength of the string. A larger wavelength (from a longer string) produces a smaller frequency, which is heard as a lower pitch.

Why should you care?

All stringed instruments produce standing waves when vibrating. All sorts of vibrating strings can be used to create instruments for the *Chapter Challenge*.

5.

For the guitar, the performer changes the tension in the vibrating strings to change the frequency while tuning the guitar. Higher tension leads to higher frequencies.

6.

Because heavier strings have greater mass, they are more difficult to accelerate than lighter strings. As a result, heavier strings will not respond as quickly to the force that is pulling the strings back and forth, thus giving a lower frequency.

7.

Preparing for the Chapter Challenge

Students will design a string instrument for use in their sound and light show. Their explanation should include the length and frequency of the standing waves produced by the string, and how the tension in the string determines the frequency and wave speed of the sound waves produced. They should also use the rubric to grade themselves.

Inquiring Further

Investigate frequency using a frequency meter

1.

Here students use a microphone input to a computer to measure the frequency of a vibrating string and see how changing the length of the vibrating string affects the frequency. Students' graphs should show that as the length of the string increases, the frequency decreases.

2.

This part repeats the exercise in *Inquiring Further*, *Question 1*, with tension taken as the independent variable. The length of the string remains the same. The graph should show the frequency increasing as the tension increases.

3.

Students repeat the exercise in *Inquiring Further*, *Question 1*, using strings of different masses, all of the same length and under the same tension. Students discover that as the mass of the string increases, the wave speed on the string decreases.

NOTES

NOTES

SECTION 3 QUIZ

5-3a **Blackline Master**

1. Which of the following will increase the frequency of a string when it vibrates?

   a) Decreasing the tension in the string.

   b) Decreasing the mass of the string.

   c) Increasing the length of the string.

   d) Decreasing the tension in the string and increasing the mass of the string.

2. A violin string is 0.64 m long. When the string is plucked, it vibrates at 256 Hz. If the standing wave produced only has a node at each end of the string, what is the wavelength of the wave on the string?

   a) 0.64 m. b) 1.28 m.

   c) 256 m. d) 0.32 m.

3. For the violin in *Question 2*, what is the speed of the wave on the string when it is plucked?

   a) 0.64 m/s b) 1.28 m/s.

   c) 328 m/s. d) 256 m/s.

4. The standing wave that is produced on a guitar string 0.90-m long has a node at each end. As the string's tension is increased, what happens to the wavelength and wave speed of the waves produced on the string?

   a) Both the wavelength and the wave speed increase.

   b) Both the wavelength and the wave speed decrease.

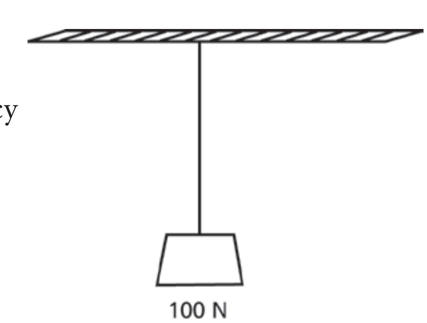
   c) The wavelength remains the same, but the wave speed decreases.

   d) The wavelength remains the same, but the wave speed increases.

5. A mass is hung from a string as shown in the diagram. When the string vibrates, it produces a wave 0.80 m long that has a wave speed of 200 m/s. What is the frequency of the wave produced?

   a) 160 Hz. b) 200 Hz.

   c) 250 Hz. d) 400 Hz.



SECTION 3 QUIZ ANSWERS

1. b) Decreasing the mass of the string will cause the string to vibrate more quickly since less mass is accelerated by the same force, leading to greater speeds. Decreasing the tension (choice *a)*) decreases the force and lowers the speed, while increasing the string length increases the wavelength, not the frequency.

2. b) With a node only at the ends, the wave on the spring will have only one loop, which is one half the wavelength. The wavelength is then twice the distance between the nodes or 1.28 m. Choice *a)* will be a common choice among students who do not recognize that one loop is only $\frac{1}{2}$ the wavelength, and choice *d)* is a reverse application of the correct answer, halving the length rather than doubling it.

3. c) The wave speed can be found from using the equation $v = f\lambda$ or $v = (256\text{ Hz})(1.28\text{ m}) = 328\text{ m/s}$.

4. d) Increasing the tension will not change the wavelength, ruling out choices *a)* and *b)* that are determined by the string length. Increasing the tension does increase the wave speed, ruling out choice *c)*.

5. c) Using the equation $v = f\lambda$ gives $200\text{ m/s} = f(0.8\text{ m})$. Solving for the frequency gives $f = 250\text{ Hz}$. Choice *a)* comes from multiplying the speed by the wavelength rather than dividing, and choices *b)* and *d)* have no merit.

CHAPTER 5