

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

— LIGO —

CALIFORNIA INSTITUTE OF TECHNOLOGY

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Educational Activity

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**Giant Slinky:
Quantitative Exhibit Activity**

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INTRODUCTION:

This activity utilizes the Giant Slinky exhibit to explore wave properties in a quantitative fashion. It is assumed that students doing this activity are **fluent in basic algebraic manipulations** and **pattern recognition**. Therefore, this activity is appropriate for **high school** students. The primary part of this activity explores transverse and longitudinal waves and their properties. This is followed by a standing wave extension activity. Finally, there is an appendix that lists the different exhibits in the LIGO SEC that also illustrate wave phenomena with brief descriptions on how they relate to the Giant Slinky.

Physics Concepts for the *Primary* Activity:

- Transverse Waves
- Longitudinal Waves
- Velocity
- Wavelength
- Amplitude
- Frequency
- Period
- Compression
- Rarefaction

Physics Concepts for the *Extension* Activity:

- Constructive Interference
- Destructive Interference
- Nodes
- Antinodes
- Fundamental
- Harmonic

Suggested Louisiana Science GLEs

[Note exceptions to the GLE definition in italic brackets after the GLE is stated.]

High School **Grades 9–12**

Science as Inquiry

The Abilities Necessary to Do Scientific Inquiry

1. Conduct an investigation that includes multiple trials and record, organize, and display data appropriately (SI-H-A2)
2. Utilize mathematics, organizational tools, and graphing skills to solve problems (SI-H-A3)
7. Choose appropriate models to explain scientific knowledge or experimental results (e.g., objects, mathematical relationships, plans, schemes, examples, role-playing, computer simulations) (SI-H-A4)

Physical Science

(Recommended for Grade 9)

Measurement and Symbolic Representation

1. Measure the physical properties of different forms of matter in metric system units (e.g., length, mass, volume, temperature) (PS-H-A1)
2. Gather and organize data in charts, tables, and graphs (PS-H-A1)

Forces and Motion

33. Calculate velocity and acceleration using equations (PS-H-E2) *[Acceleration is not calculated in this activity.]*

Interactions of Energy and Matter

41. Identify the parts and investigate the properties of transverse and compression waves (PS-H-G1)
42. Describe the relationship between wavelength and frequency (PS-H-G1)
43. Investigate and construct diagrams to illustrate the laws of reflection and refraction (PS-H-G1)
[Refraction is not discussed in this activity.]

Physics

(Recommended for Grades 11/12)

Physical Science

Measurement and Symbolic Representation

4. Perform dimensional analysis to verify problem set-up (PS-H-A1)

Interactions of Energy and Matter

25. Determine the relationships among amplitude, wavelength, frequency, period, and velocity in different media (PS-H-G1)
28. Draw constructive and destructive interference patterns and explain how the principle of superposition applies to wave propagation (PS-H-G1) *[No drawing of interference is done in this activity, but the material is covered.]*

Name: _____

Giant Slinky: Quantitative Exhibit Activity

Materials: Tape Measure, Stopwatch, & Calculator.

In this activity, we will explore wave properties using the Giant Slinky. Let's start by describing the two types of waves: transverse and longitudinal.

Transverse and Longitudinal Waves

A *transverse wave* moves side-to-side orthogonal (at a right angle; perpendicular) to the direction the wave is moving. These waves can be created on the Slinky by shaking the end of it left and right.

A *longitudinal wave* is a pressure wave alternating between high and low pressure. These waves can be created on the Slinky by gathering a few (about 5 or so) Slinky rings, compressing them with your hands and letting go. The area of high pressure is where the Slinky rings are bunched up and the area of low pressure is where the Slinky rings are spread apart.

Transverse Waves

Before we can do any math with our Slinky, we need to know a little more about its properties. Begin by measuring the length (**L**) of the Slinky (attachment disk to attachment disk). If your tape measure only measures in feet and inches, convert feet into meters using 1 ft = 0.3048 m.

Length of Slinky: L = _____ m

We must also know how long it takes a wave to travel the length of the Slinky so that we can calculate the speed of a wave. For now, we are going to investigate transverse waves, so make a single pulse by jerking the Slinky sharply to the left and right ONCE (very quickly) and then return the Slinky to the original center position. Time how long it takes the pulse to make it to the other end of the Slinky. Do this several times and average the trials together for a more accurate result. Be sure to stop any remaining waves in the Slinky in between measurements. (Table on next page.)

	Time
Trial 1	sec
Trial 2	sec
Trial 3	sec
Average time (\bar{t})	sec

Now, we can calculate the speed (v) of a *transverse* wave in this Slinky:

$$v = \frac{L}{t}$$

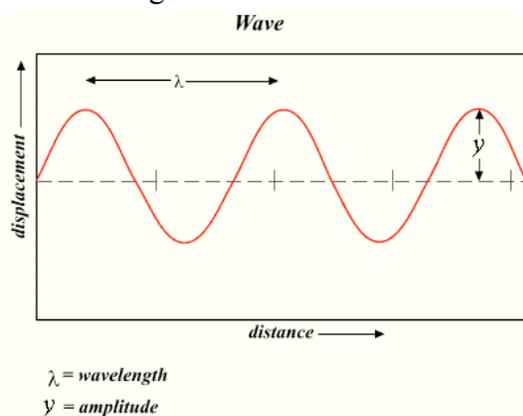
$$v = \underline{\hspace{2cm}} \text{ m/s}$$

With this information, we can now calculate wavelengths and frequencies of a wave.

Wavelength, Amplitude and Frequency

Wavelength (λ) is the distance along the direction of motion between successive peaks or valleys (maxima and minima) of a wave; note that wavelength is not the distance between a peak and the next valley, but the peak-to-peak or valley-to-valley distance. Since this is a measure of distance, wavelength will be in units of meters.

Amplitude (y) is the maximum displacement a wave makes from the rest position (in the side-to-side direction that the wave is vibrating). Note that this is half the full peak to valley distance. Amplitude is measure of distance and will have units of meters.



Frequency (f) is the count of how many wavelengths pass by a point every second. If 5 waves go by every second, then the frequency would be 5/sec. The 1/sec unit is also called a *Hertz* (Hz) and is the standard unit of frequency. The wave in the example given above then has a frequency of 5 Hz. *Period* (T) is how long it takes a wave to travel past a point and is simply the inverse of frequency ($T=1/f$) and has units of seconds.

Given the equation for speed above, derive the relationship between wavelength, frequency and wave speed.

(Hint: Wave speed will simply be v and has units of m/sec. What combination of wavelength and frequency will produce the correct units for speed? Determine this by multiplying or dividing the units of the variables for frequency and wavelength just like you would if you were substituting numbers for the variables.)

$$v = \underline{\hspace{2cm}}$$

Does the speed, frequency or wavelength of a wave depend on its amplitude?

Yes

No

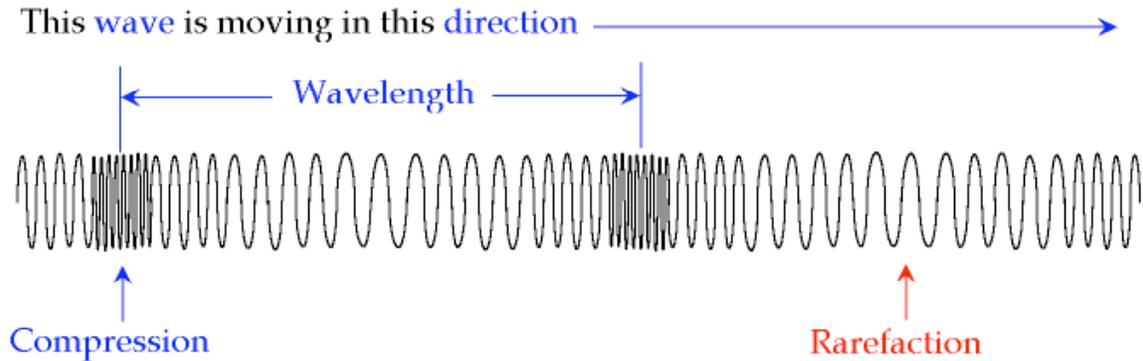
Use this relationship between wave speed, wavelength and frequency to determine what the frequency of a *transverse* wave in this Slinky would need to be in order to fit a **single wavelength along the length of the Slinky**.

$$f = \underline{\hspace{2cm}} \text{ Hz}$$

Try and make a wave with this frequency in the Slinky. As you continue to pump waves with this frequency into the Slinky, you may notice that a special pattern is starting to develop in the wave. Specifically, that there is one point in the middle of the Slinky that appears to not move at all while other parts of the wave oscillate largely. This special wave is called a *standing wave*.

Longitudinal Waves:

All of the wave properties discussed for transverse waves also apply to longitudinal waves. However, the maximum and minimum of a wave have special names: the area of high pressure (corresponding to the transverse wave's maximum) is called the *compression* and the area of low pressure (corresponding to the transverse wave's minimum) is called the *rarefaction*.



Now calculate the speed of a *longitudinal* wave in the Slinky. Gather several (about 5 or so) rings of the Slinky together. When you let go, you will see the compression travel the length of the Slinky. Time how long it takes the compression to travel the whole length (you will here the compression 'clink' against the attachment disk when it arrives at the end):

	Time
Trial 1	sec
Trial 2	sec
Trial 3	sec
Average time (\bar{t})	sec

Now, we can calculate the speed (v) of a *longitudinal* wave in this Slinky: $\left(v = \frac{L}{t}\right)$

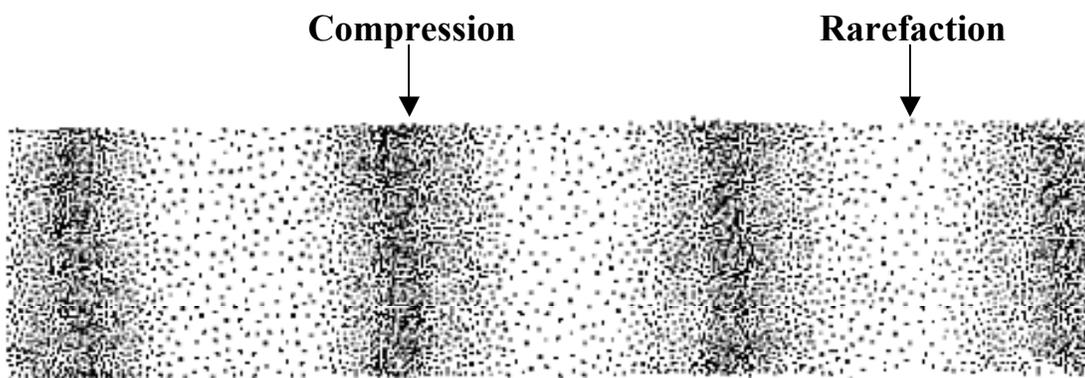
$$v = \underline{\hspace{2cm}} \text{ m/s}$$

Use this relationship between wave speed, wavelength and frequency to determine what the frequency of a *longitudinal* wave in this Slinky would need to be in order to fit ***two*** *wavelengths along the length of the Slinky*. (Be careful, this is a slightly different question than the similar one asked for transverse waves!)

$$f = \underline{\hspace{2cm}} \text{ Hz}$$

Sound

Sound waves are good examples of longitudinal waves in air. The figure below shows how molecules of air (the individual dots) are affected by sound waves. The compressions of the sound wave are areas in the air that have higher air pressure (density) and the rarefactions are areas with lower pressure (density). These alternating densities will cause our eardrums to vibrate and this is how we sense sound.



CHECK YOUR WORK

This page is not here for you to cheat, but for you to do a self-evaluation of your work AFTER you've completed this activity. After all, if your measurements are off, so will your calculations! N.B. All measurements are approximate.

These solutions are based on measurements taken on the Giant Slinky exhibit located at the LIGO SEC in Livingston, LA.

0.55 Hz
Frequency of a longitudinal wave whose wavelength is half the length of the Slinky:

2.12 m/s
Speed of a longitudinal wave in the Slinky:

3.65 sec
Time for a longitudinal pulse to travel the length of the Slinky:

0.35 Hz
Frequency of a transverse wave whose wavelength is the length of the Slinky:

No
Does the speed, frequency or wavelength of a wave depend on its amplitude?

$v = \lambda f$
Expression relating wavelength and frequency to wave speed:

2.75 m/s
Speed of a transverse wave in the Slinky:

2.81 sec
Time for a transverse pulse to travel the length of the Slinky:

7.73 m
Length of Slinky:

Image Credits:

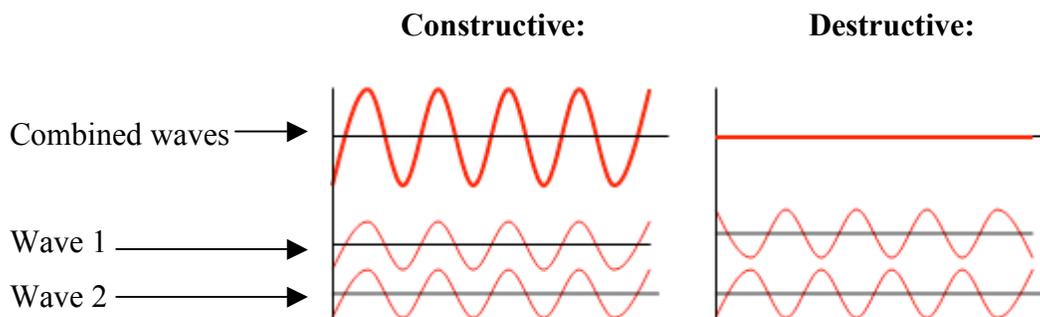
- Page 2 image from: <http://upload.wikimedia.org/wikipedia/commons/e/e9/Wave.png>, retrieved on 21 Aug 2008.
- Page 4 image from: <http://www.gcscience.com/Longitudinal-Wave.gif>, retrieved 27 Jan 2009.
- Page 5 image from: <http://scienceclass.ca/physics11/wp-content/uploads/2007/08/longitudinal.gif>, retrieved 27 Jan 2009

Standing Waves Extension:

Interference and Standing *Transverse* Waves

Interference occurs when two waves overlap each other. In the Giant Slinky, these waves are caused by the newly produced waves traveling towards one end of the Slinky and older waves that have been reflected back to the other end. When these two waves overlap, they add up to make larger and smaller amplitude waves.

- *Constructive interference* occurs when two peaks (maxima) of a wave (or two valleys/minima) overlap and add together to create a larger wave than either of the original waves.
- *Destructive interference* occurs when a peak (maximum) and a valley (minimum) overlap and add to either partially or completely cancel out the waves.

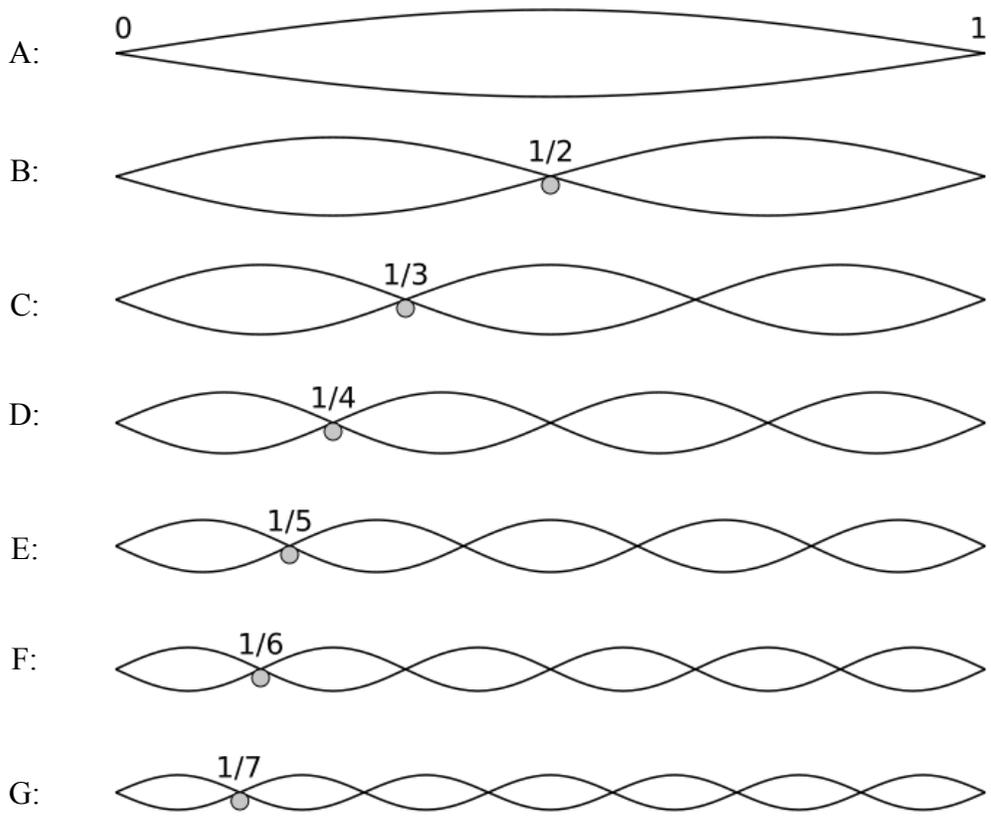


Standing waves are the result of continuous interference of waves with specific frequencies that allow for certain points of the waves to have no movement while other parts of the wave undergo all of the movement.

- *Nodes* are the places in a standing wave where there appears to be no movement.
 - *Anti-nodes* are the places in a standing wave where the maximum amount of movement (full amplitude) appears to take place.
-

The criteria to form a standing wave is that integer (whole) multiples of half a wavelength be within the length of the Slinky. When a standing wave is produced with exactly half a wavelength along the length of the Slinky, the resulting wave is called the *fundamental* and the nodes are at the endpoints of the wave. When a full wavelength is used, the resulting wave is called the *first harmonic* (B on the illustration on the next page) and a node also appears at the midpoint of the Slinky length. (If you were able to produce a standing wave with the frequency determined above, you were seeing the first harmonic wave for this Slinky.)

Label the frequencies needed to produce each of the standing waves below; the positions of the nodes are labeled according to what fraction of the Slinky length the first node that is not an end point appears. (Table on next page.)



		Frequency	
A	Fundamental		Hz
B	1 st Harmonic	(same frequency as found on page 3)	Hz
C	2 nd Harmonic		Hz
D	3 rd Harmonic		Hz
E	4 th Harmonic		Hz
F	5 th Harmonic		Hz
G	6 th Harmonic		Hz

(Hint: If λ_B is $2\lambda_A$, then $f_a = 0.5f_b$. If λ_C is $3\lambda_A$, then $f_c = 3f_a$, etc.)

Try this:

Start waving the end of the Slinky back and forth until you create a standing wave. Don't try to produce any specific frequency, just find one that is comfortable for you. Have a partner count the number of nodes and identify which harmonic is being produced. Then count how many complete back-and-forth oscillations (swings) of the Slinky you make in 10 seconds (have your partner time the 10 seconds while you count your oscillations). The frequency you are creating is then:

$$f = \frac{\text{number of oscillations}}{\text{time}}$$

where time would be 10 sec. See if the frequency you measured compares well to the frequency of your identified harmonic.

Harmonic: _____ Oscillations per 10 seconds: _____

Frequency: $f =$ _____ Hz

CHECK YOUR WORK

This page is not here for you to cheat, but for you to do a self-evaluation of your work AFTER you've completed this activity. After all, if your measurements are off, so will your calculations! N.B. All measurements are approximate.

These solutions are based on measurements taken on the Giant Slinky exhibit located at the LIGO SEC in Livingston, LA.

Try this sample results:
The 6th harmonic was produced using 12 oscillations every 10 seconds. This corresponds to a frequency of 1.2 Hz and compares well with the expected frequency from the table.

Fundamental:	0.175	Hz
1 st Harmonic:	0.35	Hz
2 nd Harmonic:	0.525	Hz
3 rd Harmonic:	0.70	Hz
4 th Harmonic:	0.875	Hz
5 th Harmonic:	1.05	Hz
6 th Harmonic:	1.225	Hz

Image Credit:

- Page 7 image from:
http://upload.wikimedia.org/wikipedia/commons/8/8a/Interference_of_two_waves.png, retrieved on 16 April 2009.
- Page 8 image from:
http://upload.wikimedia.org/wikipedia/commons/c/c5/Harmonicpartials_on_strings.svg, retrieved on 21 Aug 2008.

Appendix: Other Exhibits Illustrating Wave Phenomena

1-Dimensional Waves:

Transverse:

Vibrating String

- This illustrates the effect of changing tension on the standing waves on a string. The length is fixed between the peg and the vibrator and the frequency is fixed since the vibrator has only a single frequency. Therefore, any change in the standing waves on the string is due to the tension applied to the string.

Oscylinderscope

- When the wheel is spinning, the white lines produce a flashing light or strobe effect that allows the eye to see vibrations that would otherwise be too fast to see. This exhibit illustrates the effect that string length and tension have on standing waves.

Piano Strobe

- Like the oscylinderscope, a strobe light allows vibrations on piano strings to be visible to the eye. This exhibit shows how string length affects standing waves.

Vibrating Beams

- This exhibit illustrates how the beam material properties (e.g. density) and length affect standing waves.

Wave Machine

- This exhibit can illustrate many of the same wave properties as the Giant Slinky. All of the rods that have black ends have masses that can be moved along the rod. This will change the properties of the wave.

Longitudinal:

Making the Invisible Visible

- This exhibit visibly shows the antinodes of a sound wave (the jumping water) in a closed pipe.

Vibrating Spring

- This exhibit produces standing waves on a spring. The parts of the standing waves are even more noticeable to touch than sight. Find a node and place a finger there to feel that there is no motion at the point. Then place a finger on an antinode to feel motion.

Pipes of Pan

- This exhibit illustrates that the smaller the pipe, the higher the frequency of its fundamental standing wave. This is evidenced by higher pitch sounds coming from the shorter pipes.

2-Dimensional Waves:

Transverse:

Kettle Drum

- This exhibit uses the strobe effect to make the vibrations of the drum head visible. The complex, 2-dimensional shape of the standing waves is a result of the waves reflecting off of the edges of the drum and interfering.

Visible Vibrations

- This exhibit also illustrates 2-dimensional standing waves. The sand settles on the plates in the nodes of the standing wave. Note that the different shapes (and therefore different reflecting edges) create different standing waves for the same frequencies.