AP Physics 1 Investigation 8:
Mechanical Waves

What are the properties of mechanical waves?

Central Challenge

In this investigation, students use video analysis or other approaches to investigate the properties of mechanical waves using standing wave patterns on coiled springs and strings to determine the relationships among the following properties: frequency, wavelength, and speed.

Background

Mechanical waves are disturbances in a medium that transfer energy and momentum from one point to another without actually transferring the molecules of the medium. Longitudinal waves, such as sound waves or compressions of a spring, transfer energy and momentum through solids, liquids, and gases through oscillations of the medium that are parallel and antiparallel to the direction of propagation of energy and momentum. Transverse waves are produced by oscillations such that the motion of the medium is perpendicular to the direction of propagation within the medium. Waves produced by shaking a rope are examples of transverse waves.

The speed of propagation (v) of a mechanical wave depends on properties of the medium, such as elasticity and density, and for periodic waves (the focus of this activity), speed is equal to wavelength times frequency ($v = f\lambda$). Wavelength (λ) is the distance along the wave between two successive positions that are in the same phase (e.g., from the crest of one wave to the crest of the next wave). Frequency (f) is the number of complete oscillations per second, measured in Hertz (Hz) or inverse seconds (s^{-1}), and period (T) is the time for one complete oscillation; thus $T = 1/f$. The amplitude (A) of a wave is the maximum position of the disturbance from an equilibrium position. Nodes are positions along the wave where the amplitude is zero, and antinodes are positions where amplitude variations are at a maximum.

Wave disturbances can superimpose on each other when two or more waves arrive at the same position at the same time. The waves may constructively interfere or destructively interfere, depending on the position and phase of each wave as they meet. Standing waves are produced when wave disturbances are confined to a space in which the ongoing and reflected waves within the space form nodes and antinodes at specific positions. For example, standing waves in a tube open at both ends containing air can form such that the wavelength is twice the length of the tube. Standing waves formed on an oscillating string attached at both ends can also form such that the wavelength is twice the length of the string.

Real-World Application

Our everyday lives are full of examples in which we experience various waves such as sound waves, radio waves, light waves, microwaves, or water waves. However, students typically do not understand the physical similarities and differences between different types of waves, and do not distinguish between mechanical waves (e.g., sound) and electromagnetic waves (e.g., visible light, radio waves, microwaves). Having a solid understanding of vibrations and mechanical waves is fundamental in order for students to have a scientifically literate view of our physical world — from how we are able to hear sounds of different amplitudes and frequencies, to how musical instruments produce sounds of changing frequencies through standing waves in columns of air and on vibrating strings.

When earthquakes occur, the vibrations of the earth caused by movement in rock layers are sent in all directions. Objects such as buildings may be resonant with earthquake frequencies, causing them to vibrate at such amplitude that they break apart. The earthquake waves that travel across the surface cause transverse movements that bend bridges, roadways, tracks, and gas lines beyond their elastic limit, causing them to break.

When we talk, the vibrations of our vocal cords (as well as of our tongue, teeth, and sinuses) produce longitudinal oscillations of air that are transferred through the air to another person's ear (or another measuring instrument) so we can be heard. And when we hear, those same oscillations are transferred to the eardrum, through the middle ear to the inner ear, where nerves pick up vibrations and send them to the brain.

Many students in AP Physics are also involved in music, and this unit is a powerful opportunity to connect with those students and engage them in meaningful study.

Inquiry Overview

Using simple materials and through guided inquiry, students design a set of investigations to find the relationships among frequency, wavelength, and wave speed for transverse and longitudinal waves oscillating on a coiled spring and on a string. This lab allows students to work with waves that can be observed and manipulated. Students can see how mechanical waves behave and interact, whereas they cannot directly observe how sound waves or light waves work. These investigations with mechanical waves provide information that will be helpful in understanding sound and light (i.e., electromagnetic waves).

Students work in small groups to design their investigations and then report their findings to the class for feedback on procedure and predictions. After the initial design and report phase, student groups use the materials to investigate the following:

1. Reflection of waves: Students create both longitudinal and transverse pulses on stretched Slinkys (or coiled springs or ball-link chains) and then observe and make rules for how waves reflect from both attached ends and loose ends.

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2. Wave interference: Students send simultaneous pulses from the two ends of a Slinky, long coiled spring, or ball-link chain (transverse only) and observe what happens as the pulses pass each other.
3. Speed of pulses on a spring and string: Students use data analysis tools to film a pulse traveling on a Slinky (or alternative) to find the speed of pulses; they then compare the speeds under differing conditions, such as different materials, passing from one material to another (such as a string tied to the end of a coiled spring), or varying tension created by stretching a string or spring more or less.
4. Standing waves: Students create standing waves on a Slinky (or alternative). By varying frequency, students can observe and make measurements of wavelength related to spring length or frequency of oscillation.
5. Speed of standing waves: Students create standing waves and determine speed either by filming or using data analysis tools or measuring frequency and wavelength.

Postlab, students again report results, comparing their observations and calculations to their prelab predictions and using their conclusions to develop rules regarding the physical properties of mechanical waves.

Due to the length of time required for this complete set of investigations, you might want to split up the various parts of the investigation into shorter investigations interspersed with other lessons and activities.

Connections to the AP Physics 1 Curriculum Framework

Big Idea 6 Waves can transfer energy and momentum from one location to another without the permanent transfer of mass and serve as a mathematical model for the description of other phenomena.

Enduring Understanding	Learning Objectives
6B A periodic wave is one that repeats as a function of both time and position and can be described by its amplitude, frequency, wavelength, speed, and energy.	**6.B.2.1** The student is able to use a visual representation of a periodic mechanical wave to determine wavelength of the wave. (Science Practice 1.4) **6.B.4.1** The student is able to design an experiment to determine the relationship between periodic wave speed, wavelength, and frequency and relate these concepts to everyday examples. (Science Practices 4.2 and 5.1)
6C Only waves exhibit interference and diffraction.	**6.C.1.1** The student is able to make claims and predictions about the net disturbance that occurs when two waves overlap. Examples include standing waves. (Science Practices 6.4) **6.C.1.2** The student is able to construct representations to graphically analyze situations in which two waves overlap over time using the principle of superposition. (Science Practice 1.4)

Enduring Understanding	Learning Objectives
6D Interference and superposition lead to standing waves and beats.	**6.D.1.1** The student is able to use representations of individual pulses and construct representations to model the interaction of two pulses to analyze the superposition of two pulses. (Science Practices 1.1 and 1.4)
	6.D.1.2 The student is able to design a suitable experiment and analyze data illustrating the superposition of mechanical waves (only for pulses or standing waves). (Science Practices 4.2 and 5.1)
	6.D.1.3 The student is able to design a plan for collecting data to quantify the amplitude variations when two or more traveling waves or pulses interact in a given medium. (Science Practice 4.2)
	6.D.3.1 The student is able to refine a scientific question related to standing waves and design a detailed plan for the experiment that can be conducted to examine the phenomenon qualitatively or quantitatively. (Science Practices 2.1, 3.2, and 4.2)
	6.D.3.2 The student is able to predict properties of standing waves that result from the addition of incident and reflected waves that are confined to a region and have nodes and antinodes. (Science Practice 6.4)
	6.D.3.3 The student is able to plan data collection strategies, predict the outcome based on the relationship under test, perform data analysis, evaluate evidence compared to the prediction, explain any discrepancy, and, if necessary, revise the relationship among variables responsible for establishing standing waves on a string or in a column of air. (Science Practices 3.2, 4.1, 5.1, 5.2, and 5.3)

[**NOTE:** In addition to those listed in the learning objectives above, Science Practice 4.3 is also addressed in this investigation.]

Skills and Practices Taught/Emphasized in This Investigation

Science Practices	Activities
1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.	As part of the recording of their observations, students construct diagrams of the mechanical waves produced on strings and coiled springs, labeling nodes, antinodes, and wavelengths.
1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.	Students use their diagrams of mechanical standing waves to determine wavelengths for various situations in order to calculate frequency and/or velocity.
2.1 The student can *justify the selection of a mathematical routine* to solve problems.	Students determine what mathematical relationships describe the wavelengths for various situations (waves on a string, waves on a spring, and waves moving from one medium to another) to determine wavelengths and calculate frequency and/or wave speed.
3.2 The student can *refine scientific questions.*	Students work in groups to refine the questions posed by the teacher to testable and observable forms.
4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.	Students justify what data will be gathered, using direct measurement or video analysis.
4.2 The student can *design a plan* for collecting data to answer a particular scientific question.	Students work in small groups to design an experimental procedure for making observations and gathering data where possible to answer the questions for each part of the investigation.
4.3 The student can *collect data* to answer a particular scientific question.	Students make measurements and collect data for wavelength, period, and frequency — either directly or by using video analysis.
5.1 The student can *analyze data* to identify patterns or relationships.	Students analyze videos to determine wave speed, frequency, and wavelength or use their direct calculations to analyze their data.
5.2 The student can *refine observations and measurements* based on data analysis.	Students use their experimental observations and measurements to prepare presentations for the class during the postlab sessions. They may refine their initial predictions to come up with new conclusions about the properties of waves.
5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.	During their postlab presentations and in their written laboratory reports, students discuss the limitations to the data they acquired and include a discussion of the variables that may have affected results (such as varying amplitude and tension) from one trial to another but that were difficult to control or not considered.

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Science Practices	Activities
6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.	For the prelab presentations, students consider each of the five areas of investigation and make predictions about how the rope and Slinky will behave during particular trials.

[**NOTE:** Students should be keeping artifacts (lab notebook, portfolio, etc.) that may be used as evidence when trying to get lab credit at some institutions.]

Equipment and Materials

Per lab group (two to four students):

- Slinky or other common wave demonstrator (longer spring and tight coils with about a 1-inch diameter) or ball-link chain (2–3 meters in length; 2–3 mm diameter balls. Ball-link chain is good for creating transverse standing wave patterns; it can be found in hardware stores in varying sizes, such as the size used for lamp pull chains.).
- Thick string, such as cotton package string (2–3 meters)
- Video capture device (digital camera, smartphone, etc.).
- Video analysis or graphical analysis software: This software allows students to wirelessly collect, analyze, and share sensor data from a data sharing source.
- Meterstick
- Stopwatch (if video analysis is not available)
- (Optional) Ring stand, clamps, pulley, and calibrated masses
- (Optional) Mechanical oscillator equipment that can setup standing waves on a string

[**NOTE:** Make sure the Slinkys are in good shape with no kinks in the coils. Also, if you are unfamiliar with video analysis, see "Learning Cycle about Pulses and Waves on a Slinky" in Supplemental Resources. Typically, the longest video capture for these investigations would be 5–10 seconds.]

Timing and Length of Investigation

- **Teacher Preparation/Set-up:** 10 minutes
- **Prelab:** 20–30 minutes
- **Student Investigation:** 80–120 minutes

This time will vary based on students' familiarity with the use of video technology or their ability to devise methods to make direct measurements. They need plenty of time to develop their general rules and models for wave characteristics (30–50 minutes), construct diagrams (20–30 minutes), and make related calculations where possible (30–40 minutes).

- **Postlab Discussion:** 30 minutes

  This time is for any follow-up discussion, analysis, and student presentations of their findings. Each group should be given 3–4 minutes to present their results, both verbally and in diagrams. These presentations can include computer projections, whiteboard diagrams, or diagrams on large paper sheets.

- **Total Time:** approximately 2.5–3 hours

Safety

Remind students not to let go of the springs when stretched so that a spring does not snap up into the face of another student. As a precaution, students should wear goggles when doing this part of the lab. Otherwise there are no specific safety concerns for this lab other than general lab safety guidelines, which should always be observed.

Preparation and Prelab

Prior to the lab, small working groups should be given the purpose of the lab and introduced to available materials. Each group develops a plan for an experimental procedure to answer a set of questions related to mechanical waves. After the planning phase, each group briefly reports to the class their plan of action, with each group presenting at least one prediction about what their observations will be. The predictions can be the basis for discussion (teacher guided) that will lead to more effective laboratory designs.

Students should be familiar with the difference between transverse and longitudinal waves and with the terms *reflection*, *refraction*, *interference*, *wavelength*, *period*, *frequency*, and *wave speed*. Readings in the text can help develop a conceptual context that students will need to effectively design experiments. The PhET simulation "Wave on a String" (see Supplemental Resources), with related exercises, introduces students to concepts and works as an appropriate preparation for this lab design. The YouTube videos "Longitudinal Wave Propagation on a Slinky" by Dan Russell and "Wave Propagation Physics Demonstration" by Adam Shipley (also in Supplemental Resources) will help students visualize how to set up the Slinky.

This lab can most effectively be used as an introductory exploration for students if they have not used equations to work problems. The goal of the lab is for students to discover the relationships that will eventually lead to formulas and problem solving.

The Investigation

The basic understanding of wave properties is very important to the study of physics. Understanding the properties of sound, the physics of music, optics, modern physics, and quantum physics will all build on general ideas that students discover in the following set of experiments. As a result of this investigation, waves in columns of air can be explored more efficiently, constructive and destructive interference of waves due to diffraction can be modeled, and the interference of thin films becomes easier to understand. These typically difficult topics will be a little easier for your students after a good beginning experience with mechanical waves.

Be sure to keep your eye on proper experimental constraints during your students' experiments in this investigation. The proper length while stretching the Slinky is key (i.e., so that the Slinky oscillates easily but is not overextended), and keeping the tension or length constant between endpoints is also extremely important (since speed depends on tension). A good length for the majority of the experiments would be in the 4–5 meter range (depending on your springs or Slinkys, of course). You should practice a run or two of these experiments before students execute them in order to get a good idea of what a good experiment would look like in the lab. [**NOTE:** It is important that students consider spring length when they use springs for transverse waves, as very large amplitude waves will change the length of the spring, and therefore change the wave speed.]

Ball-link chain works very well for investigations of transverse waves, since it can be held horizontally between two students or held vertically to create an open-ended oscillation without damage to the chain. Students can also setup standing waves on the chain easily by essentially playing jump rope and turning at different frequencies to create standing waves.

In all parts, the students' experimental design should include investigations with both longitudinal and transverse waves, where possible.

Part I: The Properties of Reflection

Students anchor the Slinky to a fixed end point (another person will work), stretch the Slinky to the right length, send a couple of transverse pulses down the Slinky, and observe what happens at the fixed end. They should then determine a general rule for the property of wave reflection at a fixed end.

Next, students take the Slinky and make the other end a "moveable endpoint." This is a little trickier. They can have the Slinky attached to a long pole (broom stick, lab stand pole) and have it able to freely move up and down the pole, which is held vertically by a student or can be mounted on a lab pole stand. They can also hold a Slinky from a height, with the bottom end loose, and send transverse pulses down the Slinky, watching how they reflect at the far end. They then perform the same experiment stated above. Students should send a couple of different transverse wave pulses down the Slinky to the moveable end and observe what happens. They can then compare and contrast with the "fixed end" reflections, and again determine a general rule for these types of reflections.

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To further refine their observations (and practice for the next part of the set of experiments), students should create a 5–10 second video of a few of their pulse reflections. This video can be inserted into video analysis software or made on a cell phone or tablet. Students can slow down the process of the reflection and determine if their rules make sense and fit the video evidence.

Part II: The Properties of Interference

Using the same Slinky and video approach, students should practice sending oncoming pulses towards each other on the long stretched-out Slinky. They should vary the initial conditions; for example, on a horizontal spring, one pulse vertically upward and one pulse vertically downward, both vertically upward, and other possibilities. Or the entire investigation could take place on a smooth tile floor with either longitudinal or sideways transverse pulses. Students should strive to obtain a few good sets of video footage and use the analysis tools to understand what happens when the wave pulses are at the same positions on the spring at the same time. They should then try to come up with a general rule for combining waves.

Part III: The Speed of Wave Pulse

Prior student practice with video capture comes in handy with this particular experiment. Using the video capture/motion analysis tools or another method of determining wave speed, students should perform the following exercises:

1. Design an experimental procedure to determine if there is a relationship between the tension in the Slinky and speed of the wave pulse. [Optional: Have students try this with a thick string stretched horizontally between two ring stands and across a pulley with a calibrated mass hanging from one end. Changing the amount of mass will change the tension. Of course, students need to realize that as the amount of hanging mass changes, the string may stretch slightly, changing the linear density of the string, which will create a small error. This setup can alternatively be driven by a mechanical oscillator of known frequency so that velocity of the wave is determined by multiplying frequency and wavelength.]

2. Design an experimental procedure to determine if there is a relationship between the amplitude of the wave pulse and the speed of the wave pulse traveling through the Slinky, assuming the tension remains constant during the exercise. In order for this assumption to be valid, the amplitude of the wave pulses must be approximately the same. However, students often put a significantly different tension on the spring when they do this, which changes the speed measurably. Students then calculate large error, but it is not really an error, since the speed does change with tension. Consider this a good place to look at assumptions. Have students describe why this change in speed due to change in tension is their biggest error. [**NOTE:** One alternative method of setting this up is by using thick string stretched horizontally across a pulley with a calibrated mass hanging from one end. Tension can be controlled more easily, since it is equal to mg.]

3. Connect thick strings of different mass densities to each other and examine qualitatively how the speed of the wave changes when pulses travel from one string to another. (Again, the strings can be stretched horizontally across a pulley with a hanging mass to maintain a constant tension.) Here students use methods they used earlier to determine speed of waves applied to the waves as they pass from one string to another. [**NOTE:** Students may need some prompting to recognize that the frequency of the pulse does not change as it travels from one string to another, so speed of wave is proportional to wavelength.] This part works best when the springs/strings are laid flat on the floor and wave pulses of fairly large amplitude are produced sideways along the floor surface.

Part IV: Properties of a Standing Wave

This experiment does not require the use of video capture. The Slinky is setup between two students with a little tension. A 4–5 meter distance between the two students is usually appropriate for a double-length Slinky or about 2 meters for a standard Slinky. Have one of the two students generate wave pulses in the Slinky while the second student holds the opposite end stationary. Students should attempt to create standing waves. Have them change the frequency of their hand moving up and down or side to side. Based on their understanding of the effect of tension developed in experiment 3, they should know they want to keep the amplitude of their hand motion comparable. Get them to explicitly consider how the waves change as a student increases the amplitude or the frequency of the wave, making the spring more stretched and increasing the tension. They should take note of how these factors affect the pattern. After a little practice, students should create the following standing wave patterns:

1. First harmonic
2. Second harmonic
3. Third harmonic
4. Any others that can fit in their 4–5 meter length

Ask students the following questions:

1. What is the role of reflection and superposition in the creation of standing waves?
2. Why do you think this is called a *standing wave*?
3. Is there a pattern between the harmonics and the frequency at which the waves were generated?

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Part V: Determining Speed of a Standing Wave

This experiment attempts to determine the speed of a wave using a different approach. Students should prepare the standing wave setup as in Part 4 above. Be sure to keep the two students at a constant length apart without change during the measurements. The students should then generate standing waves in the different harmonics (1st, 2nd, 3rd, etc.). They can measure and collect data (e.g., period or wavelength) here in real time (no video slowdown needed). They then measure the wavelength of each standing wave pattern and the frequency of the waves (a stopwatch will work fine).

Students should perform the following tasks:

1. Determine a relationship between frequency and wavelength of the standing waves by first determining the period.
2. Create an appropriate set of data that will help answer the question about speed of the wave.
3. Attempt to determine the speed of the wave from a graphical interpretation of the data, along with calculations from measurements.
4. Compare this method of determination of speed with the video approach that you used in the previous method. Discuss any differences or uncertainties with both measurements.

Extension

Have students include in their written analysis of the investigation at least one application of what they learned in the experiments to how music is produced by a specific musical instrument. For example, they may choose to discuss and demonstrate how increasing the tension on a guitar string produces a standing wave on that string that is higher in pitch (frequency) because the speed is higher but wavelength remains constant. Students may choose to extend the concepts further by using standing waves in air columns and choosing to discuss and demonstrate an instrument such as a flute or clarinet. They should be specific about how the oscillations are produced in the instrument they select and should discuss for that instrument how wavelengths and frequencies are related to instrument length. This is an important extension that makes this investigation relevant to students.

Common Student Challenges

One of the most widely held student misconceptions about mechanical waves is the idea that the changing of one of the wave characteristics (amplitude, frequency, etc.) will change the speed of the wave. This set of small inquiry experiments should help students overcome that misconception. The use of the video and the ability for students to see for themselves how the properties play out at a scale that can be seen with the help of video analysis is clearly an advantage for the discovery of correct wave mechanics.

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Be sure to pay attention to proper scale and uncertainty of measurements. These are areas where students typically have difficulty early in their learning of experimental methods. Error in their measurements and uncertainty in their data collection should be considered. Sometimes students will not realize that 12.6 m/s and 12.8 m/s are really the *same speed* within the limitations of their experimental design.

When examining the effect of tension in a string or spring on speed of wave, students may not know how to control for the change in length that goes along with change in tension. You can simply allow students to address this as a source of error in the experiment. With more advanced students, however, you might want to guide them to come up with a correction for the change in linear density, using the formula:

$$v = \sqrt{\frac{T}{\mu}}$$

where v is velocity of the wave, T is the tension, and μ is the linear density of the string (mass of string divided by length of string). For example, if the string is stretched to one and a half times its original length, its linear density is two-thirds as great.

Students may have difficulty using computer video analysis — consider providing a lesson on the use of this technology so it becomes an option for students on this lab.

Analyzing Results

Having each group present their work to the entire class will reinforce good scientific thinking, collaboration, and the ownership of ideas. The pressure for students to be part of a peer team and share with their peers will help foster a unique classroom culture and certainly create the good habits that help create a scientific community.

The details of the properties of mechanical waves should get fleshed out by all of the student presentations and the follow-up questions by their peers. If there are poorly designed experiments or data, students' questioning will certainly point this out to the larger class. Eventually, through the process of sharing and discussion (with teacher supervision), the correct ideas of the properties of waves will make their way throughout the classroom. Follow-up the postlab presentations by asking groups to repeat poorly designed experiments or certain parts of the experiment if small-group or large-group conclusions conflict or are not clear.

If student presentations or discussions seem to be missing key elements, consider prompting them with the following questions:

- What is the difference between how transverse and longitudinal waves appear as standing waves?

- How did you control your experiment to keep tension as constant as possible when not actually testing for it as a variable?
- How can period and wavelength be used to calculate wave speed?
- What did you observe when a pulse passed from one type of medium to another (e.g., from the coiled spring to the string)?
- How did changing the amplitude of pulses affect frequency, wavelength, and wave speed?
- What rule did you make for wavelengths of standing waves on a spring, chain, or string fixed at both ends? What rule did you make for standing waves for a spring, chain, or string fixed only at one end?
- What did you conclude about how waves reflect at an open end versus how they reflect at a fixed end of a spring, string, or chain?

Students should prepare labeled diagrams for what they observe in each part, and they may want to also prepare diagrams on whiteboards or large paper for their postlab presentations. They should have written summaries of their predictions, observations, and conclusions for each of the five parts of the investigation. They should also have calculations or use equations found from their prelab resources to illustrate how quantities change quantitatively (using proportional reasoning) for each of the five parts.

Assessing Student Understanding

After completing this investigation, students should be able to articulate how they participated in the scientific process as they designed experiments and engaged in activities around the properties of mechanical waves. Students should have experienced and demonstrated:

- Making observations;
- Posing and refining scientific questions;
- Creating experimental designs; and
- Sharing experimental results with their peers and/or a larger community.

Students should also be able to:

- Describe factors that affect the speed of wave propagation;
- Define and describe, using correct terminology, the general characteristics of mechanical waves;
- Describe how to create a standing wave;
- Sketch and verbally describe the relationship of the harmonic number to wavelength and frequency in a standing wave;
- Describe the process of wave superposition; and
- Describe how waves reflect and how they behave when passing from one medium to another.

Assessing the Science Practices

Science Practice 1.1 The student can *create representations and models* of natural or man-made phenomena and systems in the domain.

Proficient	Provides complete, correctly labeled diagrams showing harmonics and/or wave patterns for each part of the investigation.
Nearly Proficient	Provides diagrams for each part of the investigation with some labels missing or some incorrect.
On the Path to Proficiency	Provides diagrams for observations and also labels the diagrams.
An Attempt	Makes an attempt to describe harmonics for standing waves, but does not provide complete diagrams and diagrams are not labeled.

Science Practice 1.4 The student can *use representations and models* to analyze situations or solve problems qualitatively and quantitatively.

Proficient	Uses diagrams of harmonics or wave pulses to present clear explanations of patterns in each part of the investigation.
Nearly Proficient	Makes a good attempt to relate standing wave diagrams and diagrams of harmonics to written explanations of patterns in those diagrams.
On the Path to Proficiency	Makes an attempt in some parts of the investigation to provide written explanations to accompany diagrams of waves and/or standing wave patterns.
An Attempt	Provides only sketchy written explanations for a few diagrams of wave patterns or standing waves.

Science Practice 2.1 The student can *justify the selection of a mathematical routine* to solve problems.

Proficient	Calculates wave speeds from direct measurement or video analysis. Develops mathematical relationships for harmonics on a spring or string.
Nearly Proficient	Makes calculations for wave speed from measurements and makes an attempt to derive mathematical relationships among standing wave patterns for different harmonics.
On the Path to Proficiency	Makes some calculations for wave speed or develops proportional reasoning for changes in wave speed with occasional or minor errors.
An Attempt	Calculates wave speed from wavelength and period/frequency with significant errors.

Science Practice 3.2 The student can *refine scientific questions.*

Proficient	For the prelab presentation, comes up with appropriate, well-worded experimental questions addressing each of the five challenge areas for the investigation.
Nearly Proficient	For the prelab presentation, comes up with experimental questions for the five challenge areas, needing only small changes or corrections prior to actual experimentation.
On the Path to Proficiency	For the prelab presentation, develops experimental questions for several of the proposed challenges.
An Attempt	For the prelab presentation, takes a step toward developing an experimental question for the investigation for at least one of the proposed challenges.

Science Practice 4.1 The student can *justify the selection of the kind of data* needed to answer a particular scientific question.

Proficient	Justifies what data will be gathered — using direct measurement or video analysis — and what is described will lead to meaningful results for calculations of wave speed.
Nearly Proficient	Justifies what data will be gathered — using direct measurement or video analysis — but what is described contains occasional or minor errors, such as if measuring wavelength and frequency for standing waves but measurement of period instead of frequency will be necessary instead.
On the Path to Proficiency	Justifies what data will be gathered — using direct measurement or video analysis — but what is described has some flaws that need to be corrected prior to actual investigation.
An Attempt	Makes an attempt to justify what data to gather — using direct measurement or video analysis — but what is described will not lead to meaningful results.

Science Practice 4.2 The student can *design a plan* for collecting data to answer a particular scientific question.

Proficient	Presents plans for collecting data during the prelab that are appropriate for all five parts of the investigation, and the plans will lead to appropriate gathering of observations and data related to properties of waves.
Nearly Proficient	Presents plans for collecting data during the prelab that are appropriate for four of the five parts of the investigation but need some minor suggestions or corrections in order to lead to appropriate gathering of observations and data related to properties of waves.
On the Path to Proficiency	Presents plans for collecting data during the prelab that are appropriate for two or three of the five parts of the investigation.
An Attempt	Presents a plan for collecting data during the prelab that is appropriate for only one of the five parts of the investigations.

Science Practice 4.3 The student can *collect data* to answer a particular scientific question.

Proficient	Collects complete and well-organized data, and the data is clearly connected to the questions asked about properties of waves.
Nearly Proficient	Collects complete data and the data are well organized, but attempts to connect the data to the questions asked about properties of waves are incomplete or inaccurate.
On the Path to Proficiency	Collects data from all trials, but the data is disorganized or lacking units and no attempt is made to connect the data to the questions asked about properties of waves.
An Attempt	Collects some data, but the data is incomplete and/or disorganized and no attempt is made to connect the data to the questions asked about properties of waves.

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Science Practice 5.1 The student can *analyze data* to identify patterns or relationships.

Proficient	Accurately calculates wave speeds from direct measurement or from video analysis. Develops mathematical relationships for harmonics on a spring or string, and makes accurate conclusions regarding relationships among wave speed, frequency, and wavelength.
Nearly Proficient	Makes accurate calculations for wave speed from measurements, and makes an attempt to derive mathematical relationships among standing wave patterns for different harmonics. Proposes mostly accurate conclusions relating wave speed, wavelength, and frequency.
On the Path to Proficiency	Makes some accurate calculations for wave speed or develops proportional reasoning for changes in wave speed. Proposes some accurate conclusions regarding relationships among wave speed, frequency, and wavelength from investigations.
An Attempt	Inaccurately calculates wave speed from wavelength and period/frequency, and makes incomplete or inaccurate conclusions regarding relationships among wave properties.

Science Practice 5.3 The student can *evaluate the evidence provided by data sets* in relation to a particular scientific question.

Proficient	During the postlab presentation, clearly evaluates the validity of the data, or the method(s) used to gather the data, and the evaluation is correct and meaningful; for example, recognizes how changing one variable, such as amplitude, also affects tension in the spring or string and addresses how this affected the results.
Nearly Proficient	During the postlab presentation, evaluates the validity of the data, or the method(s) used to gather the data, but the evaluation has some flaws; for example, recognizes that changing one variable, such as amplitude, also affects tension in the spring or string but unable to describe how.
On the Path to Proficiency	During the postlab presentation, evaluates the validity of some of data, or the method(s) used to gather the data, but the evaluation is flawed; for example, does not recognize how changing one variable, such as amplitude, also affects tension in the spring or string.
An Attempt	During the postlab presentation, makes an attempt to evaluate the validity of the data, or the method(s) used to gather the data, but the evaluation is not meaningful.

Science Practice 6.4 The student can *make claims and predictions about natural phenomena* based on scientific theories and models.

Proficient	In the extension, correctly and completely explains how a specific (selected) musical instrument works using the terminology and concepts investigated in this lab.
Nearly Proficient	In the extension, explains how a particular musical instrument works using correct terminology from the investigation, but the explanation has some flaws that need correction.
On the Path to Proficiency	In the extension, makes an attempt to explain how a particular musical instrument works using the concepts and terminology from the investigation, but there are flaws in the explanation.
An Attempt	In the extension, makes an attempt to explain how the investigation relates to a musical instrument, but the explanation is not complete or not valid.

Supplemental Resources

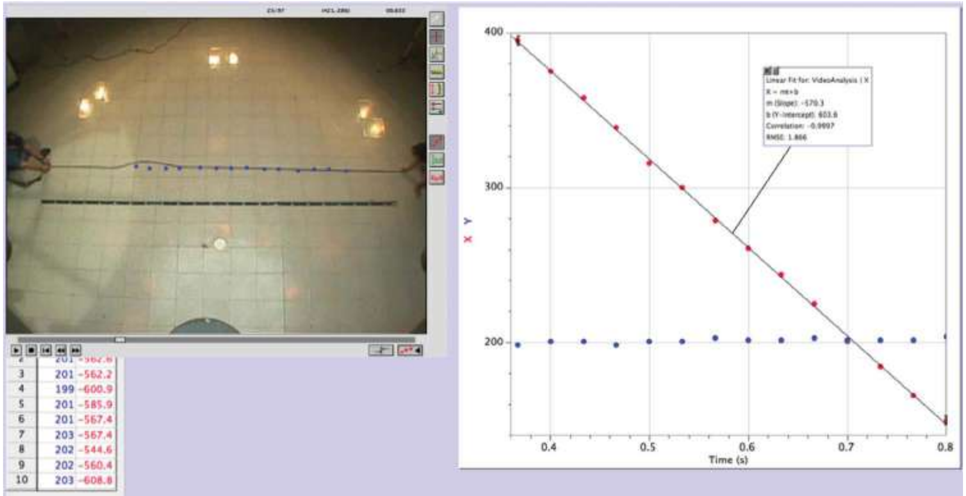
Kryjerskkaia, Mila, MacKenzi R. Stetzer, and Paula R. L. Heron, "Student Understanding of Wave Behavior at a Boundary: The Relationships among Wavelength, Propagation Speed, and Frequency." *American Journal of Physics* 80, no. 4 (2012): 339–347.

"Learning Cycle about Pulses and Waves on a Slinky." Rutgers, The State University of New Jersey. Accessed September 1, 2014. http://paer.rutgers.edu/pt3/experimentindex.php?topicid=6&cycleid=12.

"Longitudinal Wave Propagation on a Slinky." Russell, Dan. Accessed November 17, 2014. http://www.youtube.com/watch?v=y7qS6SyyrFU

"Vibrating String." HyperPhysics. Georgia State University. Accessed September 1, 2014. http://hyperphysics.phy-astr.gsu.edu/hbase/waves/string.html. [*This site has definitions and interesting examples of harmonics on a string that could be used in preparation for this lab or as a formative assessment.*]

"Wave on a String." PhET. University of Colorado Boulder. Accessed September 1, 2014. http://phet.colorado.edu/en/simulation/wave-on-a-string. [*This site provides a good prelab introduction and is an excellent resource if you are unable to implement computer video analysis. It is possible to create a more "low tech" alternative to these investigations by using this site, which has several videos of these experiments. The students can use the videos to make observations (qualitatively and quantitatively), although not as precise as with video analysis. The videos can even be downloaded to a computer and used in the video analysis. The image on the next page (captured from a video on the Rutgers site and uploaded into the video analysis tool) shows what this would look like.*]



"Wave Propagation Physics Demonstration." Shipley, Adam. Accessed November 17, 2014. http://www.youtube.com/watch?v=xt5q3UOfG0Y

Wittman, Michael C., Richard N. Steinberg, and Edward F. Redish. "Making Sense of How Students Make Sense of Mechanical Waves." *The Physics Teacher* 37, no. 1 (1999): 15–21. [*This article gives the physics teacher a handle on many of the student difficulties in understanding the properties of mechanical waves.*]