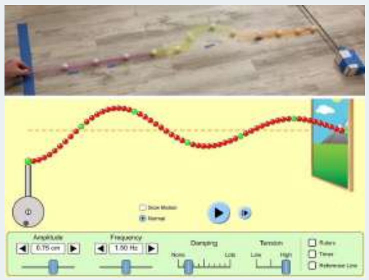
Lesson 3: How does energy transfer through a wave?

Previous Lesson *We studied the Microwave Oven Manual and inferred that the oven's magnetron produces microwave radiation. We watched a video, read about the magnetron, and used energy transfer models to connect new ideas about fields to our prior understanding. We wondered how the changing electric fields connect to waves, and decided to look into waves in more detail.*

This Lesson

Investigation

3 days



Adapted from: PhET Interactive Simulations

We recall examples of physical waves. We produce waves with a spring. We develop a model for how physical waves transfer energy through solids. We use a computer simulation to plan and carry out four investigations. Using our results, we make claims about how various wave properties affect energy transfer. We develop a mathematical model of the relationship between frequency, wave speed, and wavelength.

Next Lesson *We will investigate how moving electrons in an antenna cause energy transfer. We will use and evaluate different representations of electromagnetic radiation, and read about how vibrating charged particles generate electric and magnetic fields. We will develop an explanation of electromagnetic radiation and use it to predict interactions with matter inside the microwave oven.*

BUILDING TOWARD NGSS

HS-PS2-5, HS-PS4-1, HS-PS4-2, HS-PS4-3, HS-PS4-4, HS-PS4-5, HS-ESS2-4

What students will do

3.A Plan and conduct an investigation to produce data to serve as evidence to support claims about how certain wave properties affect energy transfer in waves. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.A.1, PS4.B.1)

3.B Use algebraic techniques to develop a mathematical model to identify and test the relationship between frequency, wave speed, and wavelength. (SEP: 5.3; CCC: 1.4; DCI: PS4.A.1)

What students will figure out

- When the first particle in the wave on a string is moved (as a force is applied to it, which transfers energy to it), it stretches the electric field (bond) between it and the next particle.
- When a bond is stretched (or compressed), energy is transferred to the fields that produce the bond, and when it is unstretched (or uncompressed), that energy transfers out of the fields and back into the motion of the particles around it.
- A larger amplitude means that the electric fields (bonds) between particles will be stretched farther in either direction in a given amount of time (period); this increase in vibration speed transfers more energy along the wave.
- A larger frequency means that the bonds will be stretched back and forth more times per second; this increase in vibration speed transfers more energy along the wave.
- The wavelength of a wave can be determined by the wave speed across the medium and its frequency.

Part	Duration		Summary	Slide	Materials
1	2 min		**NAVIGATE** Highlight wave thinking as a theme in some of the exit tickets from Lesson 2. Recall examples of other kinds of waves.	A	
2	5 min		**INTRODUCE A SLINKY SPRING WAVE MODEL** Recall prior use of a simulation from *Earth's Interior Unit* for exploring particle and bond/field interactions. Introduce a slinky spring model.	B	M-E-F poster, computer with access to https://openscied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html, painters tape
3	8 min		**CARRY OUT AN INVESTIGATION OF WAVES** Conduct an investigation in small groups to produce single waves across a chain of balls and slinky springs, and discuss observations in those groups.	C	Slinky Spring Wave Investigation
4	5 min		**ANALYZE AND INTERPRET WAVE DATA** Discuss the investigation questions in a Scientists Circle. Use a slinky station setup to represent and analyze a wave, its direction of motion, and the motion of a single particle in the system.	D	chart paper, 8.5" x 11" paper, markers, slinky spring station
5	12 min		**DEVELOP AN ENERGY TRANSFER MODEL** Stay in a Scientists Circle to develop a particle-level model to explain how energy is transferred by waves across solid matter.	E-H	M-E-F poster, chart paper, markers
6	4 min		**NAVIGATE TO A COMPUTER SIMULATION INVESTIGATION** Identify what we would be able to visualize, measure, and change in a computer simulation of the physical system we manipulated in class.	I	
7	9 min		**EXPLORE A WAVE ON A STRING SIMULATION AND NAVIGATE** Observe wave pulse behavior in the computer simulation. Individually explore the behavior of the system when the motion is driven by an oscillating source, and begin to identify variables.	J-K	*Wave Simulation Observations*, https://www.openscied.org/general/waveonastring/

End of day 1

8	20 min	**NAVIGATE: IDENTIFY WAVE VARIABLES** Identify and operationally define the variables that can be controlled and/or observed/measured in the simulation. Record these on a poster with words, drawings, and mathematical expressions.	L-M	*Wave Simulation Observations*, Physical Wave Properties poster, markers
9	8 min	**PREDICT WAVE PROPERTY RELATIONSHIPS** Use the cards to sort out and discuss predicted variable relationships, and record them on the *Wave Property Relationships* handout.	N	*Wave Property Relationships*, *Wave Variable Cards*, Physical Wave Properties poster
10	9 min	**CARRY OUT INVESTIGATION OF AMPLITUDE AND CONSTRUCT EXPLANATIONS** Use the simulation to conduct an investigation of amplitude in partners. Record conclusions about what wave properties are affected by changing amplitude and whether energy transfer is affected.	O-P	
11	8 min	**COMPARE EXPLANATIONS FOR AMPLITUDE** Compare explanations for amplitude in a whole-class discussion. Record the consensus for these on a poster.	Q	*Wave Property Relationships*, Physical Wave Properties poster, Relationships Between Physical Wave Properties poster, markers, https://www.openscied.org/general/waveonastring/
				End of day 2
12	6 min	**INVESTIGATE FREQUENCY AND CONSTRUCT EXPLANATIONS** Use the simulation to conduct an investigation of frequency in partners. Record conclusions about what wave properties are affected by changing frequency and whether energy transfer is affected.	R-S	
13	5 min	**COMPARE EXPLANATIONS FOR FREQUENCY** Compare explanations for frequency in a class discussion. Record the consensus for these on the Relationships Between Physical Wave Properties poster.	T	*Wave Property Relationships*, Physical Wave Properties poster, Relationships Between Physical Wave Properties poster, markers, https://www.openscied.org/general/waveonastring/
14	8 min	**INVESTIGATE TENSION AND DAMPING AND CONSTRUCT EXPLANATIONS** Use the simulation to conduct an investigation of tension and damping. Record conclusions about what wave properties are affected by tension or damping and whether energy transfer is affected.	U-V	

15	8 min		**COMPARE EXPLANATIONS FOR DAMPING AND TENSION** Compare explanations for damping and tension in a whole-class discussion. Record the consensus for these on the Relationships Between Physical Wave Properties poster.	W	Physical Wave Properties poster, Relationships Between Physical Wave Properties poster, markers, https://www.openscied.org/general/waveonastring/
16	12 min	☑	**DEVELOP A MATHEMATICAL MODEL FOR WAVELENGTH** Use the simulation results and mathematical definitions of the variables to create an equation for wavelength in a whole-class discussion.	X-Y	Relationships Between Physical Wave Properties poster, markers
17	6 min	☑	**NAVIGATE: ASSIGN AN ELECTRONIC EXIT TICKET** Complete an Electronic Exit Ticket about which variables affect the amount of energy transferred by a wave.	Z	Relationships Between Physical Wave Properties poster, markers

End of day 3

Lesson 3 • Learning Plan Snapshot

Lesson 3 • Materials List

	per student	per group	per class
Slinky Spring Wave Investigation materials		• slinky spring station • painters tape	
Lesson materials	• *Wave Simulation Observations* • science notebook • *Wave Property Relationships*	• *Wave Variable Cards*	• M-E-F poster • computer with access to https://openscied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html • painters tape • chart paper • 8.5" x 11" paper • markers • slinky spring station • https://www.openscied.org/general/waveonastring/ • Physical Wave Properties poster • Relationships Between Physical Wave Properties poster

Materials preparation (20 minutes)

Review teacher guide, slides, and teacher references or keys (if applicable).

Make copies of handouts and ensure sufficient copies of student references, readings, and procedures are available.

Three-hole-punch all handouts so they can be added to students' notebooks.

Test the simulation: https://www.openscied.org/general/waveonastring/

Post the M-E-F poster from *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)* in a location where it can be seen and referenced in this lesson.

Prepare the following posters:

- Title a piece of chart paper "Physical Wave Properties" and create a T-chart with the headings "Control" and "Observe/measure".
- Title a piece of chart paper "Relationships Between Physical Wave Properties".

Make a copy of *Wave Variable Cards* for each group of 4 in your largest class, to reuse between classes:

- Make these copies on thicker stock paper if possible.
- Cut out the cards in each deck.
- Clip the cards together with a paper clip.

Before class, make a copy of the Electronic Exit Ticket found in the following link: https://docs.google.com/forms/d/1KZSjCY9jgE6TnfMEDRg4m_s729XOyyZ1JozUnyTgxsO/copy. Share the link to the **copy** with students, **not** the link provided here; if you share the original link, that will create a new copy for each student, and you will not have access to their responses. See *Unknown material with identifier: pr.l3.tref2* for how to create an Electronic Exit Ticket.

Day 1: Slinky Spring Wave Investigation

- **Group size:** 5 students.
- **Setup:** Prepare 1 slinky spring station per group as outlined in *Slinky Spring Station Preparation* and/or watch this supplemental teacher video outlining these directions: https://youtu.be/fFl-pX-MflE

Lesson 3 • Where We Are Going and NOT Going

Where We Are Going

The focus of this lesson is to develop an understanding of wave properties using physical waves on a slinky spring and a simulated string, in order to build toward PS4.B.1:

- Electromagnetic radiation (e.g., ~~radio,~~ microwaves~~, light~~) can be modeled as a wave ~~of changing electric and magnetic fields or as particles called photons~~. The wave model is useful for explaining many features of electromagnetic radiation~~, and the particle model explains other features~~.

In this lesson, we develop a model of physical waves that will be used in later lessons to help students understand (1) electromagnetic radiation as a wave and (2) the energy transferred by it.

This lesson also targets PS3.A.4:

- These relationships are better understood at the microscopic scale, at which all of the different manifestations of energy can be modeled as either motions of particles or energy stored in fields (which mediate interactions between particles). ~~This last concept includes radiation, a phenomenon in which energy stored in fields moves across space.~~

We investigate the energy of a physical wave in terms of the motion of particles and the energy stored in fields within the bonds between particles. This builds on the work in *OpenSciEd Unit P.2: How forces in Earth's interior determine what will happen to its surface? (Earth's Interior Unit)* on electric fields that can store energy. Our consideration of the energy of moving particles builds on the introduction of kinetic energy in *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)*. The transfer of energy between fields and kinetic energy builds on our consideration of energy transfer for orbiting objects in *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*.

Another disciplinary core idea (DCI) targeted by this lesson is:

- PS4.A.1 The wavelength and frequency of a wave are related to one another by the speed of travel of the wave, which depends on the type of wave and the medium through which it is passing.

This builds on the consideration of the speed of waves through different materials, established in *Earth's Interior Unit*.

This lesson helps coherently develop two science and engineering practices (SEPs) that are intentionally developed in this unit:

- 3.2: Plan and conduct an investigation individually and collaboratively to produce data to serve as the basis for evidence, and in the design: decide on types, how much, and accuracy of data needed to produce reliable measurements and consider limitations on the precision of the data (e.g., number of trials, ~~cost, risk,~~ time), and refine the design accordingly.
- 6.1: Make a quantitative and/or qualitative claim regarding the relationship between dependent and independent variables.

We support SEP 3.2 through collaboratively identifying independent and dependent variables and providing structures for students to record their process. We further support it by suggesting a number of trials for the first simulation investigation (amplitude) and then provide gradual release of this scaffold, by having students reevaluate and refine their procedure for collecting data in light of limitations they encountered in the first investigation when they plan and carry out the second, third, and fourth investigations (frequency, tension, and damping). We support students in communicating claims by providing a sentence stem that scaffolds clear use of independent and dependent variables. They will continue to work on planning and conducting investigations in future lessons.

This lesson also has students engage with using mathematics and computational thinking:

- 5.3: Apply techniques of algebra and functions to represent and solve scientific and engineering problems.

These elements were also developed across two prior units: *OpenSciEd Unit P.3: What can we do to make driving safer for everyone? (Vehicle Collisions Unit)* and *OpenSciEd Unit P.4: Meteors, Orbits, and Gravity (Meteors Unit)*.

Students co-develop definitions for the following words in this lesson: *amplitude, frequency, wavelength, wave speed*. Students encounter the following words: *damping, tension.* **Do not** post any words or ask students to add them to their Personal Glossaries until after the class has developed a shared understanding of their meaning.

Where We Are NOT Going

This lesson focuses on physical waves. To continue the development of PS4.B.1 and PS3.A.4, the next lesson will develop ideas about electromagnetic radiation as changing electric and magnetic fields, and how microwave radiation transfers (moves) energy across space.

An extension opportunity described at the end of this lesson allows interested students to return to the slinky spring system, to test how increasing the tension in the spring (by extending the spring's stretch and the corresponding location of the tape) affects the speed of the waves traveling through it. This could involve collecting data and graphing quantitative relationships (e.g., amount of stretch/tension in the spring versus wave speed). This will further support developing the understanding of PS4.A.1 and provide additional practice with SEPs 3.2 and 6.1.

LEARNING PLAN for LESSON 3

1 · NAVIGATE

2 min

MATERIALS: None

Navigate using exit tickets to define new vocabulary. Present **slide A**. Say, *I read through your exit tickets, and I saw a lot of ideas about what happens between the magnetron antenna and the light bulbs to transfer energy all the way across the microwave oven. A lot of you wrote about radiation, or microwave radiation, or electromagnetic radiation. What does it mean when we use these words?* Have students turn and talk for a minute about each of the words on the slide: ✱

- electromagnetic
- microwave
- radiation

Say, *We don't yet know exactly what microwave radiation is, but because we do know about some other kinds of waves, exploring them could be a productive way to try to understand it. Scientists often look at related phenomena to develop a model to help understand something new. Maybe we can find some properties of waves that are the same no matter what kind of wave it is, and that can help us figure out how microwave radiation transfers energy. What other kinds of waves could give us some clues about this?*

Accept a few quick ideas, for example: ocean waves, slinkies, radio waves, light waves, sound waves.

✱ ATTENDING TO EQUITY

Supporting emergent multilinguals: It can be very helpful for all students, particularly emergent multilinguals, to break down compound words like *microwave*. Prompt students to reason about the first part by asking, *What does "micro" mean to you? What other words have you heard that use the prefix micro?* They will probably say "microscope." Encourage them to make connections to uses of the prefix *micro* in other languages. Then summarize the idea of putting both words together--*micro* and *wave*--to make a single compound word indicating that this particular wave is smaller than other waves we may encounter.

2 · INTRODUCE A SLINKY SPRING WAVE MODEL

5 min

MATERIALS: M-E-F poster, computer with access to https://openscied-static.s3.amazonaws.com/HTML+Files/Apply+and+Remove+External+Force+on+a+Solid.html, painters tape

Review a computer model we have used in the past. Display **slide B**. Explain that we are going to use a physical manipulative to explore wave behavior through a solid. Remind students that during *Earth's Interior Unit*, we used a simulation to model what happens inside solids as external forces are applied to them.

Give students a moment to think about the questions on the slide. Then discuss them as a class, using the table below. Follow up with the third question about M-E-F connections related to the springs.

Suggested prompt	Sample student response
What did the spheres represent?	The particles that make up a solid. Atoms or molecules.
What did the lines between them represent?	Bonds. The fields between particles that produce the forces that keep them held together.
How did the simulation help us visualize the relationship between forces, energy, and matter at a particle level?	(Accept all answers.)

Reference the M-E-F poster. Remind students that the simulation was one of a few types of visualization tools we used to see these relationships more clearly, so we could better understand how energy was transferred into, stored in, and then transferred back out of the electric fields between the particles as a solid was compressed or stretched.

Introduce the slinky spring physical model. Hold up one end of the slinky spring at one of the stations. Say that we will use this manipulative today for initial explorations of wave behavior through physical matter. Ask where the particles that make up that matter are located in this system. Students should point to the styrofoam balls glued inside the slinky spring.

Explain that just like in *Earth's Interior Unit*, the slinky spring represents the bonds between these particles, and the entire length of the spring represents a long, thin section of solid matter. Say that when students get to their stations, they will see that one end of the spring is hooked over a bar and that a piece of tape shows how far to stretch the other end. Point out that the particle at the end you are holding is marked with an X.

Emphasize that the tape represents the maximum length they should pull that particle to, to ensure the spring doesn't permanently deform, but that they can move it anywhere along the tape.

3 · CARRY OUT AN INVESTIGATION OF WAVES

8 min

MATERIALS: Slinky Spring Wave Investigation
Frame the wave investigation. Display **slide C**. Read the directions aloud: • *Pull the first particle on the slinky spring to the tape line. Move it back and forth along the tape* ***once*** *to try to make a single wave travel down the slinky spring. Repeat this a few times and discuss:* 1. *What is the shape of the wave?* 2. *How did the particles along it move?* 3. *What was transferred to the end of the slinky spring?* Ask a few students to revoice the goal for the investigation. Listen for them to suggest re-creating a wave using the slinky spring and observing how it transfers energy. Remind students that because their group also needs to discuss the three questions in the relatively short time available for the investigation, they should try to have a different group member take a turn every minute or so to ensure that everyone has an opportunity to explore the spring's behavior. **Carry out the wave investigation.** Assign students to small groups and send them to their stations to complete the investigation as described on the slide.

4 · ANALYZE AND INTERPRET WAVE DATA

5 min

MATERIALS: chart paper, 8.5” x 11” paper, markers, slinky spring station

Discuss the answers to the investigation questions. Display **slide D**. Convene a Scientists Circle, with one of the slinky spring setups on the floor or a central table to use as an interactive manipulative as needed throughout the class discussion. Discuss the answers to the questions that students considered in their groups, along with follow-up questions, as shown in the tables below.

Suggested prompt	Sample student response	Follow-up question
What was the shape of the wave?	A rounded hill.	*How could we tell where one end of the wave starts and where the other ends?*
If we could freeze time, what would that wave look like?	A curved section in one part of the slinky spring.	

Adjust the shape of the slinky spring on the floor to represent the shape of a wave.

Suggested prompt	Sample student response
How did the particles (styrofoam balls) within the system move (as waves traveled through it)?	Back and forth. The same way you moved the particle (foam ball) at the end of the slinky spring.
How does this compare to the direction of the wave?	The wave went forward along the spring, perpendicular to the particles.

To visualize the motion that students describe, draw a dotted line ending with a dual arrowhead line on a piece of 8.5” x 11” paper and place it next to one of the styrofoam balls in the slinky spring, showing the ball’s path of motion (perpendicular to the spring). Label this “the path of a particle". Add a second piece of paper with a solid arrow on it showing the direction the wave travels along the spring, and label this "the path of the wave".

Suggested prompt	Sample student response	Follow-up question
What was transferred to the last particle at the end of the system?	Motion. Energy.	*How do we know that some energy was transferred to the last particle on the end of the system when the wave reached it?*

Emphasize that **no matter** (represented by the styrofoam balls) was transferred to the end of the system in this process, as all the matter moved perpendicular to the direction of the wave and then returned to its starting position after the wave was transmitted through it.

5 · DEVELOP AN ENERGY TRANSFER MODEL

12 min

MATERIALS: M-E-F poster, chart paper, markers

Motivate developing a diagrammatic model of energy transfer. Suggest that we try to apply our M-E-F thinking to this system, to help use the particle-level model to explain how energy is transferred across solid matter when a wave moves through it.

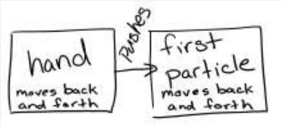
Establish and model how energy is transferred into the system. Display **slide E**. Use the prompts on the slide and in the table below to establish how energy is transferred into the system (by a hand or other contact force).

Suggested prompt	Sample student response
How did we transfer energy into the system?	By moving our hand back and forth.
What force interactions happened between our hand and the first particle it was holding as we did this?	There were contact forces on both things.

Remind students that we saw waves in *Earth's Interior Unit*, called seismic waves, moving through Earth. Ask, *What kinds of force interactions are needed to initiate seismic waves, and how do they transfer energy?* Listen for ideas such as:

- Tectonic plates push on each other during an earthquake.
- They use the bond between the particles of matter.

On chart paper, draw the first two boxes of the model and the related annotations and arrow connecting them. Leave enough space to the right to add four more boxes and arrows in later steps.



Model energy transfer between the particles through fields. Display **slide F**. Pose the first question:

- *How is energy transferred from the first particle to the second particle?*

Students will say it is transferred through the slinky spring. Remind them that the spring is an analogy for a bond, and that we can use the spring to visualize the force interactions occurring across the electric fields that produce the bonds between atoms and molecules in solid matter.

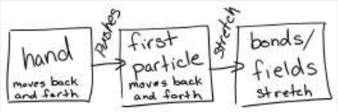
Suggest we try to show the state of the entire system a split second after the first particle has been pushed away from its starting position. Ask for a few volunteers to come up to the slinky spring system. Have one volunteer pull the first particle and hold it a few inches away from its starting position as a second volunteer holds down the second particle so it remains in its starting position. Ask students what happens to the shape of the spring. They will say it stretches.

Identify energy storage in the system. Pose the second question on the slide:

- *Is any energy stored in the system at this point in time?*

Students should recall that energy is stored in the spring now (or in the fields between the particles). If they don't, point out that there is no kinetic energy in the system, and ask what would happen if either volunteer released their particle. Students will say it would move. If needed, you can test that. The point of such a test is to establish that energy is stored in the fields when the spring is stretched and is then transferred out of the fields/bonds to the particles as the spring pulls back together.

Add the next box (bond/fields) on the model and the annotated arrow going to it to represent energy transfer into bonds/fields.



Motivate modeling wave shape. Explain that we could keep modeling the system one particle at a time, thinking about how energy is transferred from one particle to a bond/field and then to the next particle and so on. Emphasize, however, that thinking about the system as a single particle at a time won't help us capture the wave-like pattern moving through the matter.

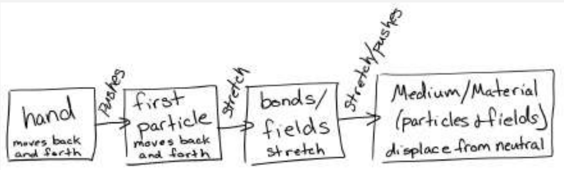
Suggest that instead, we try to re-create the general shape of that wave we saw moving through the system, but at a slightly later point in time. Ask a volunteer to hold down particles 1 and 2, another to hold down particles 4 and 5, and a third to pull particle 3 a few inches to the side of the system. Ask students to describe how this shape resembles what we saw in the wave.

Display **slide G**. Pose the first question on the slide:

- *Is any energy stored in the matter at these points in time?*

They should say yes, because the slinky springs are stretched. Again, you could release these particles to provide evidence of this, if needed.

Suggest thinking about a collection of particles. Say, *Let's represent this part of the system together, so we can refer to collections of particles that are changing across it. When scientists refer to the matter that a physical wave is moving through, they call it the medium.*

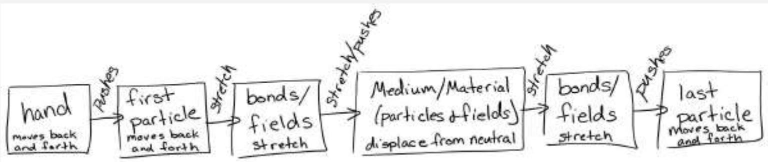


Add the middle box (medium/materials) to the diagram and add the annotated arrow going to it.

Pose the second question on the slide:

- *How is energy transferred from the medium to the last particle?*

Students will say through the stretch of the slinky spring or through the stretch of the bonds/fields. Add the last two boxes, related arrows, and annotations on the right of the transfer model as shown.



Turn and talk about changing the amount of energy transferred. Display **slide H**. Cue students to use this model as they talk with a partner about these questions:

- *How can we change the amount of energy transferred by a wave through this system?*
- *What are the limitations of our slinky spring for further exploration of this question?*

After giving them a minute to talk, have students share their ideas. Listen for them to suggest we could move our hand back and forth faster.

Remind students that speed is a measure of two variables: the distance traveled in a certain amount of time. Ask about two examples related to each of these variables for changing wave speed:

- *If we keep the time it takes to move our hand back and forth as a constant, then which of these would speed up the wave: increasing the distance we moved it, or decreasing the distance we moved it?*
    - Increasing the distance we moved it.
- *If we keep the distance we move our hand back and forth as a constant, then which of these would speed up the wave: taking more time, or taking less time, to move it back and forth?*
    - Taking less time.

6 · NAVIGATE TO A COMPUTER SIMULATION INVESTIGATION

4 min

MATERIALS: None

Propose simulation attributes. Display **slide I**. Remind students that scientists sometimes create a computer simulation of a system when they want to make controlled observations of its behavior under different conditions, and that we've also taken such an approach in previous units.

ALTERNATE ACTIVITY	To support additional coherence for students, you could ask them to share a couple of examples of when we've used simulations in previous units.

Pose the questions on the slide and have students discuss them with a partner for 2 minutes (don't use time to report out):

- *What would you want to be able to visualize or measure in a computer simulation of the waves on the particle slinky spring system we used in class?*
- *What variables would you want to be able to change?*

Say that you have a simulation that you are hopeful will meet many of their criteria, but you want to give students a few minutes to explore it to determine what its capabilities are and any limitations it may have before deciding what--if any--investigations we might be able to do with it.

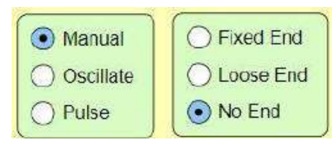
7 · EXPLORE A WAVE ON A STRING SIMULATION AND NAVIGATE

9 min

MATERIALS: *Wave Simulation Observations*, https://www.openscied.org/general/waveonastring/

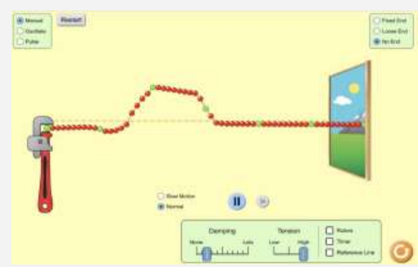
Explore the wave simulation. Display **slide J**. Launch the simulation: https://www.openscied.org/general/waveonastring/. Adjust the simulation settings as shown below:

Waves on a String simulation action:	Open the simulation and select the **"Manual"** and **"No End"** settings at the top. • Use the mouse to drag the wrench up and back down to the start position to produce a single wave pulse. • After the first pulse has left the system, repeat the motion of the wrench. Leave the simulation open for continued use.



Pose the question on the slide:

- *How does the behavior of this simulated system compare to the physical manipulatives we just used?*



Listen for responses such as:

- It produces similarly shaped waves.
- There are more particles in the system.
- It looks like there is something like a slinky spring between the particles.

Point out that though its initial behavior has many similarities to the physical system we used in class, the simulation also has the ability to keep moving the initial particle back and forth.

✱ SUPPORTING STUDENTS IN ENGAGING IN PLANNING AND CARRYING OUT INVESTIGATIONS

Remind students that their work throughout this lesson has been a reflection of the nature of science: Scientific Investigations Use a Variety of Methods. Help students realize that scientists often use physical models and simulations because they are important tools in scientific research. Physical models allow direct observation of changes in a system that result from manipulating variables of interest, such as amplitude and frequency, and simulations enable them to study complex phenomena, such as particle behavior in a string, to further our understanding.

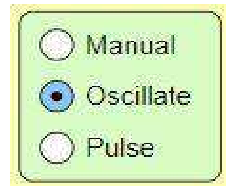
✱ ATTENDING TO EQUITY

Universal Design for Learning: The *Wave Simulation Observations* handout provides a graphic and concept organizer to guide student noticing and comprehension throughout working with the simulation and

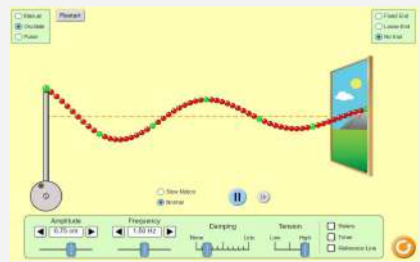
Connect to the behavior of the electrons in the microwave oven. Say, *Let's remind ourselves of what we know about how the electrons are moving in the magnetron. How does their movement compare to the movement I just made with the wrench?* Students should say they keep moving (or vibrating) back and forth (rather than moving only briefly or once).

Explain that this is where the simulation helps us visualize what is happening more precisely, when we simulate a continuous back-and-forth motion at the source, than the spring can. Emphasize that this is because the simulation allows us to pause and freeze what we're seeing as we run it in a continuous back-and-forth motion (oscillation). It also allows us to have no end to our string, which enables us to isolate a single wave pattern. ✱

Hover over the "Oscillate" menu option and explain that this setting will enable the simulation to produce continuous vibration of the first particle, on the left end of the system.

Waves on a String simulation action:	• Select **"Oscillate"** in the top right box and let the simulation run for a few seconds. • Pause the simulation using the **pause** button below the wave. 

Ask students what they noticed about the object on the left. They will say it changed to a circle and a stick, and it kept moving. Tell them that when the simulation is running with this oscillation setting, it produces a back-and-forth motion on the left side of the system, by turning the circle the rod is connected to at a constant rate; and that in turn, it lifts and lowers that stick and repeats this with each rotation, similarly to the way our legs move up and down on bike pedals when a bike wheel below them rotates around.



Tell the class they have a few minutes to explore the simulation under these settings to see what else it has that allows us to visualize or measure in it, and what other variables it allows us to manipulate.

Explore variables in the simulation. Present **slide K**. Review the settings to keep unchanged for this exploration: "Oscillate" and "No End". Say, *We want to use this simulation to investigate what affects the amount of energy transferred by a wave. Let's start by figuring out what we can control, observe, or measure.*

Waves on a String simulation action:	Students use the simulation individually. They should:

discussing the variables. This structuring of *representations* of information aids students in distinguishing important and unimportant information.

	- Keep the top settings on "**Oscillate**" and "**No End**". - Explore all other settings/controls.

Distribute the *Wave Simulation Observations* handout to each student. Encourage them to explore the rest of the controls in the simulation and what variables they can observe about the wave. Introduce *Wave Simulation Observations* as a place to organize and document their thinking about variables they can control and/or observe/measure in this simulation. Encourage them to label parts of the image in whatever way helps them think, and to use the back of the handout for any additional drawings they want to record. ✱ Give them about 5 minutes to make observations of the simulation.

Remind students to store their handout in their science notebook at the end of class.

End of day 1

8 · NAVIGATE: IDENTIFY WAVE VARIABLES

20 min

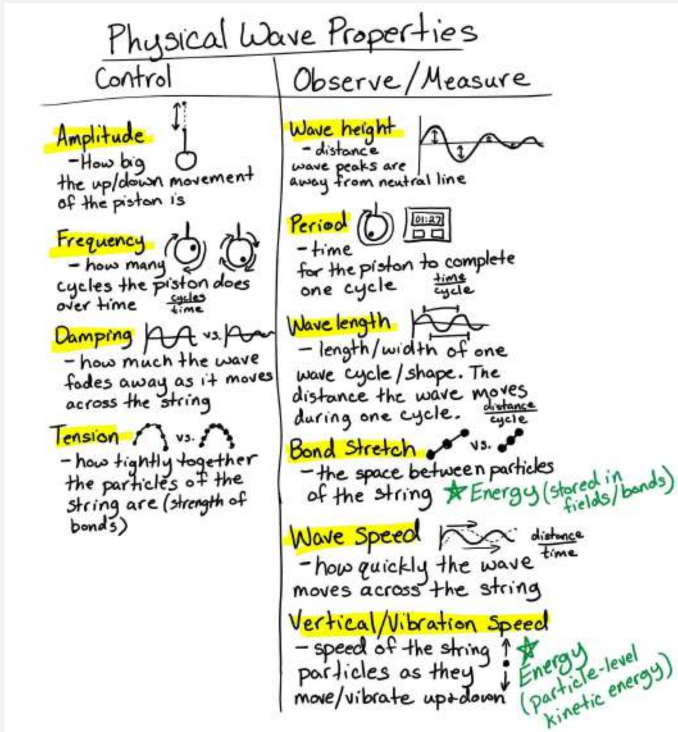
MATERIALS: *Wave Simulation Observations*, science notebook, Physical Wave Properties poster, markers

Revisit the identified wave property variables. Ask students to take a moment to review what they wrote on their *Wave Simulation Observations* handout yesterday, so we can establish consensus on all the variables in the simulation we could investigate further.

Present **slide L**. Have the class gather in a Scientists Circle. ✱ Make the Physical Wave Properties poster and markers available.

Operationally define these variables. Ask students to share things they could control (amplitude, frequency, ✱ damping, and tension) or observe/measure (wave height, period, wavelength, bond stretch, wave speed, vertical/vibration speed) in the simulation. Encourage multiple students to weigh in on collectively deciding how these variables should be defined and visually represented. ✱ Have them write or draw consensus ideas on the poster, as you facilitate reaching consensus around what we are representing and how we are describing it.

As students build consensus around a representation for a variable, feel free to introduce the canonical word as a synonym for whatever they initially named it. For example, they might have called the variable "wavelength" something like "width of the repeating shape"; this can be labeled "width of the repeating shape (wavelength)".



If needed, display the simulation and change a setting, or have a volunteer change things based on students' suggestions or variables that still need to be added.

Waves on a String simulation action:	Have the simulation available in case students would like to see or try something.

✱ ATTENDING TO EQUITY

Building classroom culture and Community Agreements: As this is the fifth unit in the sequence, it is assumed that the work students have previously done on refining and revisiting Community Agreements has become an established routine, with fading scaffolding. At this point, having students take on greater leadership in facilitating and documenting a discussion is a natural progression. However, if you are doing this unit out of sequence, a more intentional revisiting of those Community Agreements before starting this discussion may be helpful.

✱ ATTENDING TO EQUITY

Supporting emergent multilinguals: As students identify frequency as a variable, help them make connections to the everyday ways they use the word. Ask, *If you are getting a high frequency of text messages, what does that mean?* Listen for ideas about how it means a lot of text messages coming close together. Help students see the connection between this everyday use and the scientific definition, which means almost the same thing. A high-frequency wave is a wave pattern that passes by a single point

ADDITIONAL GUIDANCE	If every observable variable isn't developed in this discussion, more can be added as needed in the discussion after the first investigation. The more important goal is to co-construct these definitions for things we noticed as a class, rather than trying to pre-define these variables if students haven't noticed them.

ADDITIONAL GUIDANCE	When discussing variables, it is helpful to use "cycle" to refer to one revolution of the piston driver. This allows a common term to define frequency, period, and wavelength. Having common language across variables will help in later conversations. The symbols that represent each value are not as important here as a conceptual understanding of these quantities and how/why they are related. If you decide to ask students to remember T (period) and λ (lambda, wavelength), you can introduce them here, and have students record them in their Personal Glossaries.

ASSESSMENT OPPORTUNITY	**What to look for/listen for in the moment:** Listen for students to discuss how to: ● Represent frequency, wavelength, and wave speed mathematically in terms of a fraction or an equation (e.g., frequency = cycles/time). (SEP: 5.3; CCC: 1.4; DCI: PS4.A.1) **What to do:** Writing frequency, wavelength, and wave speed as equations or using definitions in fraction form (as seen in the example poster above) will be helpful when developing the equation for wavelength toward the end of the lesson. (This can also be done for period, but that isn't critical for future conversations.) If students don't represent the variables this way, encourage them to do so to make sense of the variables. Give them one example and have them create these representations for the other variables. **Building toward: 3.B** Use algebraic techniques to develop a mathematical model to identify and describe the relationship between frequency, wave speed, and wavelength. (SEP: 5.2, 5.3; CCC: 1.4; DCI: PS4.A.1)

Connect the variables to energy transfer. Once the poster has been created, display **slide M**. Say, *We wanted to look at a simulation that would help us explore energy transferred by waves.* Read the question on the slide:

- *Which of the variables directly connect to the energy that is in the medium as the wave travels through it?*

Listen for students to say vertical/vibration speed and bond stretch. These are related to the stretch in the slinky spring and the motion of the particles back and forth in the previous investigation. Have a volunteer note this on the poster.

very frequently, or more times per second. A low-frequency wave is a wave pattern that passes by a single point less frequently, or fewer times per second.

✱ ATTENDING TO EQUITY

Universal Design for Learning: This lesson makes use of multiple media with the simulation, handout, and chart of words and images. This provides multiple ways that students see information *represented* and can *express and communicate* their understanding. Using multiple forms of media to present and make sense of information provides more access for the diverse learners in your classroom.

Say, *Let's use the simulation to investigate how the variables we can control affect the energy transferred by the wave.*

9 · PREDICT WAVE PROPERTY RELATIONSHIPS

8 min

MATERIALS: *Wave Property Relationships*, *Wave Variable Cards*, Physical Wave Properties poster

Predict relationships between variables. Display **slide N**. Distribute a deck of *Wave Variable Cards* to each group and a copy of *Wave Property Relationships* to each student. Cue students to work with the cards and follow the directions on the handout as they discuss and record predictions for the relationships between the wave properties.

ALTERNATE ACTIVITY	If your students do not need the scaffold of the *Wave Variable Cards* to help make sense of variable relationships, you may opt to skip their use.

ASSESSMENT OPPORTUNITY	**What to look for/listen for in the moment:** Listen/look for students to: • Use cards to predict how certain wave properties affect each other. (SEP: 3.2; DCI: PS4.A.1, PS4.B.1) • Plan how to investigate the relationships between wave properties, including energy, by selecting independent variables and dependent variables to test. (SEP: 3.2; CCC: 5.2; DCI: PS4.A.1, PS4.B.1) **What to do:** If students are unsure about which variables can be independent variables, remind them that independent variables are the ones we can control, and refer them to the Physical Wave Properties poster. **Building toward: 3.A.1** Plan and conduct an investigation to produce data to serve as evidence to support claims of how certain wave properties affect energy transfer in waves. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.A.1, PS4.B.1)

10 · CARRY OUT INVESTIGATION OF AMPLITUDE AND CONSTRUCT EXPLANATIONS

9 min

MATERIALS: None

Investigate amplitude in the simulation. Display **slide O**. Instruct students to carry out their investigations of amplitude in partners using *Wave Property Relationships*. Share the simulation link: https://www.openscied.org/general/waveonastring/. Remind students to keep the settings on "Oscillate" and "No End". Encourage them to collect no fewer than three and no more than five data points for each investigation. Give partners 5 minutes to carry out the investigation and record their results in column D of the table on *Wave Property Relationships*.

Waves on a String simulation action:	Students use the simulation with partners. They should: ● Keep the top settings on "**Oscillate**" and "**No End**". ● Investigate what variables change when **amplitude** is changed. ● Collect 3-5 data points for each test.

Construct explanations for amplitude. Display **slide P**. Using the prompt and example sentence stem on the slide (*When ______ (decreases/increases), then _______*), ask students to work with their partner to write a conclusion statement for amplitude and then record this statement on the back of their handout. ✱ The slide also reminds them to address how changing amplitude affects energy transferred by the wave.

✱ ATTENDING TO EQUITY

Supporting emergent multilinguals: Before whole-class discussions, it can be helpful to provide students an opportunity to work with others in pairs, triads, or small groups on ideas related to their reasoning. This can especially benefit emerging multilingual students because smaller group structures offer a chance to engage in sensemaking with peers, as well as a space to use their linguistic and nonlinguistic resources to express their ideas (and learn from other students' uses of these resources, too).

11 · COMPARE EXPLANATIONS FOR AMPLITUDE

8 min

MATERIALS: *Wave Property Relationships*, Physical Wave Properties poster, Relationships Between Physical Wave Properties poster, markers, https://www.openscied.org/general/waveonastring/

Compare explanations for amplitude. Be sure the Physical Wave Properties poster is displayed. Present **slide Q**. Put up the chart paper titled "Relationships Between Physical Wave Properties". Use the prompts on the slide to facilitate consensus building:

- *How does changing amplitude affect the other variables?*
- *How can we visually represent this?*
- *Does changing amplitude affect how much energy is transferred by the wave?*
    - *If so, does increasing amplitude increase or decrease the energy transferred?*

If many students did not see the expected changes, display the simulation https://www.openscied.org/general/waveonastring/, show both a small and a large amplitude, and ask students to explain their observations.

Waves on a String simulation action:	If needed: Display the simulation with the top settings on "**Oscillate**" and "**No End**". • Set **amplitude** to a small, non-zero value. • Change **amplitude** to a large value. • Ask students to explain their observations of what changes.

ADDITIONAL GUIDANCE

Integrating this idea into this model provides an opportunity to integrate understanding from MS-PS4-1 (Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave) and to develop more than a descriptive model of the relationship between amplitude and energy. The focus here is to layer in a deeper mechanistic understanding of why this relationship exists (for physical waves) from a matter-and-forces perspective as well.

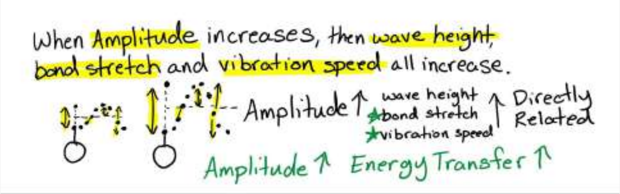
Some students may also recognize that increases in particle speed are related to the kinetic energy equations from their prior unit, *Meteors Unit*. If students completed the *OpenSciEd Unit 8.2: How can a sound make something move? (Sound Unit)* in middle school, they might make connections to some of the mathematical relationships developed in that unit between amplitude and energy as well. Such connections are not the focus of this unit, but you might hear, for example, something like: "Because kinetic energy grows with the square of the speed of a particle or object, the energy of the wave would be proportional to the square of the

✱ SUPPORTING STUDENTS IN ENGAGING IN USING MATHEMATICS AND COMPUTATIONAL THINKING

To align with Common Core terminology, you may choose to say that the variables are "proportionally related" or "inversely proportional". Consult with your students' math teachers about how they are referring to these types of relationships, and help students make the connection if your terminology is different.

amplitude. This is because double the amplitude in the same amount of time would necessitate that the particles in the system are traveling twice as fast (on average)."

Document amplitude findings on the new poster. Once consensus is reached, write a conclusion statement on the Relationships Between Physical Wave Properties poster, similar to the example below. Then use student ideas to create a visual representation of this relationship on the poster; optionally, have a volunteer do the drawing.



If necessary, add variables to the Physical Wave Properties poster. Consider adding other representations, such as using arrows or directly related language, as in the example.

Finally, using student responses to the slide's third prompt, indicate on the Relationships Between Physical Wave Properties poster which dependent variables are related to energy transfer, and write a statement or symbolic representation of how changing amplitude changes the energy transferred by a wave (see the example to the right). ✱

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Listen for students to:

- Use their data to make claims about how increasing amplitude increases bond stretch and vibration speed. (SEP: 6.1; DCI: PS3.A.4, PS4.B.1)
- Use bond stretch and vibration speed data to claim that increasing amplitude increases the energy transferred by a wave. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.B.1)

What to do: If students struggle to see the relationships between variables, show the simulation, walk through an example of small amplitude and one of large amplitude, and ask about the properties on the Physical Wave Properties poster.

Building toward: 3.A.2 Plan and conduct an investigation to produce data to serve as evidence to support claims of how certain wave properties affect energy transfer in waves. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.A.1, PS4.B.1)

End of day 2

12 · INVESTIGATE FREQUENCY AND CONSTRUCT EXPLANATIONS

6 min

MATERIALS: None

Investigate frequency in the simulation. Display **slide R**. Remind students to keep the settings on "Oscillate" and "No End". Ask them to take a moment to consider the limitations of time and the number of trials needed to establish relationships, and to refine their investigation design given that they will only have about 4 minutes to collect data on frequency.

Give students the 4 minutes to carry out the investigation and record their results in column D of the table on *Wave Property Relationships*.

Waves on a String simulation action:	Students use the simulation with partners. They should: • Keep the top settings on "**Oscillate**" and "**No End**". • Investigate what variables change when **frequency** is changed.

Construct explanations for frequency. Display **slide S**. Using the prompt and example sentence stem on the slide (*When ______ (decreases/increases), then _______*), ask students to individually write a conclusion statement for frequency and record it on the back of *Wave Property Relationships*. The slide also reminds them to address how changing frequency affects energy transferred by the wave.

13 · COMPARE EXPLANATIONS FOR FREQUENCY

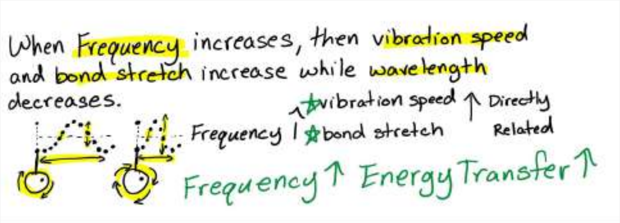
5 min

MATERIALS: *Wave Property Relationships*, Physical Wave Properties poster, Relationships Between Physical Wave Properties poster, markers, https://www.openscied.org/general/waveonastring/

Compare explanations for frequency. Present **slide T**. Return to the Relationships Between Physical Wave Properties poster. Use the prompts on the slide to facilitate consensus building:

- *How does changing frequency affect the other variables?*
- *How can we visually represent this?*
- *Does changing frequency affect how much energy is transferred by the wave?*
    - *If so, does increasing frequency increase or decrease the energy transferred?*

Document the frequency findings on the poster. Once consensus is reached, write a conclusion statement on the poster, similar to the example below. Then use student ideas to create a visual representation of this relationship on the poster, optionally having a volunteer do the drawing. Consider adding other representations, such as arrows or directly related language.



Finally, using student responses to the slide's third prompt, indicate which dependent variables are related to energy transfer, and write a statement or draw a symbolic representation of how changing frequency changes the energy transferred by a wave.

14 · INVESTIGATE TENSION AND DAMPING AND CONSTRUCT EXPLANATIONS

8 min

MATERIALS: None

Investigate damping and tension in the simulation. Display **slide U**. Remind students to keep the settings on "Oscillate" and "No End". Ask them again to take a moment to consider the limitations of time and the number of trials needed to establish relationships, and to refine their investigation design given that they need to collect data for two variables (damping and tension) in 5 minutes. Give partners the 5 minutes to carry out the investigations and record their results in the table.

Waves on a String simulation action:	Students use the simulation with partners. They should:

	• Keep the top settings on "**Oscillate**" and "**No End**". • Investigate what variables change when **damping** or **tension** is changed.

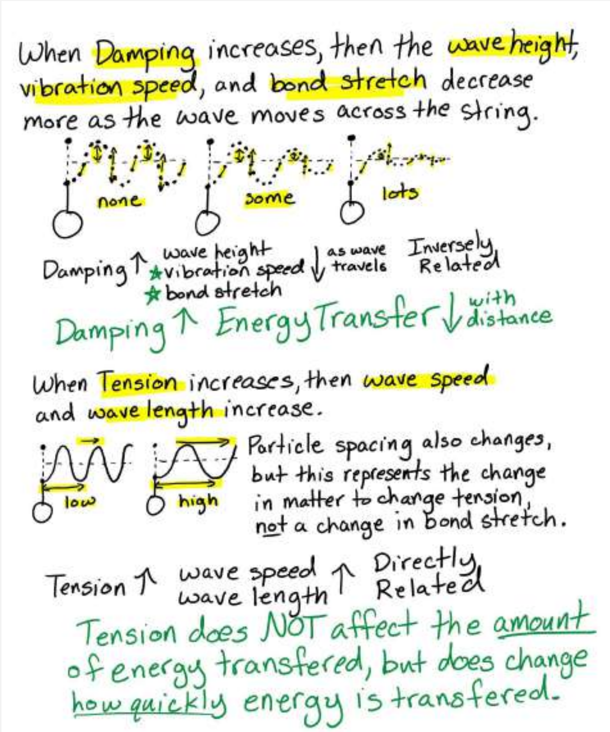
Construct explanations for damping and tension. Display **slide V**. Using the prompt and example sentence stem, ask students to individually write conclusion statements for both damping and tension and record them on the back of *Wave Property Relationships*. The slide also reminds them to address how changing these variables affects energy transferred by the wave.

MATERIALS: Physical Wave Properties poster, Relationships Between Physical Wave Properties poster, markers, https://www.openscied.org/general/waveonastring/

Compare explanations for damping and tension. Return to the Relationships Between Physical Wave Properties poster. Present **slide W**. Use the prompts to facilitate consensus building for both damping and tension:

- *How does changing damping or tension affect the other variables?*
- *How can we visually represent this?*
- *Does changing damping or tension affect how much energy is transferred by the wave?*
    - *If so, does increasing damping and/or tension increase or decrease the energy transferred?*

Document damping and tension findings on the poster. Once consensus is reached, write a conclusion statement for each on the poster, similar to the examples below. Then use student ideas to create visual representations of these relationships on the poster. Finally, using student responses to the slide's third prompt, indicate which dependent variables are related to energy transfer, and write a statement or draw a symbolic representation of how changing damping and tension changes the energy transferred by a wave (see example to the right).



ADDITIONAL GUIDANCE	When discussing tension, be sure to mention that the distance between the particles cannot be used as a measurement of bond stretch or energy if the tension is changed. This is because such a change would show the change in the matter of the string based on tension, as opposed to a stretch due to wave energy. Students may also think that a faster wave has more energy, similar to how an object that moves faster has more kinetic energy. Remind them that the wave is not matter: it is energy transferred through the matter of the string. Tension does affect how quickly the energy is transferred, but can't change the amount of energy

	transferred, because that would break the law of conservation of energy, based on changing the amount of energy compared to the input energy.

16 · DEVELOP A MATHEMATICAL MODEL FOR WAVELENGTH

12 min

MATERIALS: Relationships Between Physical Wave Properties poster, markers

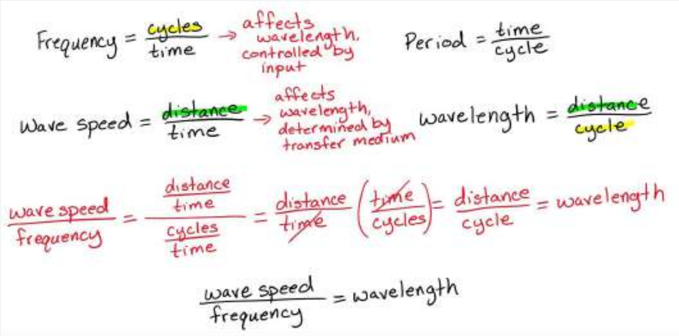
Orient to mathematical expressions for variables. Present **slide X**. Read the top of the slide:
Scientists sometimes create mathematical models to quantitatively describe the relationships between variables. Then pose the first question:

- *Can we use our results plus our definitions of the variables to create any equations to relate our variables?*

Refer students to the Relationships Between Physical Wave Properties poster. Listen for them to suggest considering the variables that we defined with fraction or equation forms on the poster. If they do not, guide them to these variables (frequency, period, wavelength, and wave speed) by rewriting their definitions as equations on the board.

Use variable expressions to build a mathematical relationship. Ask students to take a few minutes to consider these equation definitions and which of these variables they found to cause changes in others. Then ask for some ideas. Listen for them to identify that both frequency and wave speed (through tension) affected the wavelength, and that these definitions all include the same parts.

Ask for suggestions on how to combine frequency and wave speed in a way that would cancel out time, as it is the part that wavelength doesn't have. If students suggest using period, guide them to use only the controllable variables to derive the wavelength. Listen for the suggestion to divide wave speed by frequency. Using student ideas, show on the board that this results in wavelength (see the example image below).



Evaluate whether the data supports the equation we developed. Pose the slide's follow-up question:

- *Is this equation supported by our data and conclusions?*

Ask students to explain how this equation is or is not supported. Listen for them to say that increasing wave speed caused an increase in wavelength, and increasing frequency caused a decrease in wavelength, so their locations in the equation make sense and are supported by the data. If they suggest that period and frequency can be related, that is fine to discuss as well, but it is not critical.

Collect the *Wave Property Relationships* handout.

ASSESSMENT OPPORTUNITY	**What to look for/listen for:** Listen/look for students' verbal and written responses to: • Show planning of the investigation within the table of wave property variables and predicted outcomes, including connections to energy transferred by the wave. (SEP: 3.2; CCC: 5.2; DCI: PS4.A.1, PS4.B.1) • Document the process of the investigation, including how and what data was collected and observations used as evidence for the conclusion statements on the back. (SEP: 3.2) • Show claims on how wave properties affect the energy transferred by the wave are connected to and supported by the data from the investigation. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS4.B.1) • Show claims about energy transferred by the wave are connected to the vertical motion of particles and energy in stretched fields in bonds. (SEP: 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.B.1) **What to do:** Read through students' work on *Wave Property Relationships* and provide written feedback. If students still struggle with the relationships, take time at the beginning of the next class to review the Relationships Between Physical Wave Properties poster, with an emphasis on the energy transfer connections. **Building toward: 3.A.3** Plan and conduct an investigation to produce data to serve as evidence to support claims about how certain wave properties affect energy transfer in waves. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.A.1, PS4.B.1)
ADDITIONAL GUIDANCE	Students may need a reminder that wave speed is actually a controllable variable, indirectly, through adjusting the tension. If they are stuck on this, take a moment to review how changing tension is changing the medium through which the wave travels, and how we know that this is what determines the speed of a wave. Remind them that we saw this in *Earth's Interior Unit*, with waves traveling at different speeds through various types and densities of materials in Earth's mantle.
ALTERNATE ACTIVITY	**Optional extension:** If time permits, test the mathematical model. Display **slide Y**. Assign different tensions for groups to set in the simulation, make note of the corresponding wave speed produced, and then test at least two frequencies at that tension setting to see whether the resulting wavelength is predicted by the equation we developed.

17 · NAVIGATE: ASSIGN AN ELECTRONIC EXIT TICKET

6 min

MATERIALS: Relationships Between Physical Wave Properties poster, markers

Navigate with an Electronic Exit Ticket. Display **slide Z**. Before class, make a copy of https://docs.google.com/forms/d/1KZSjCY9jgE6TnfMEDRg4m_s729XOyyZ1JozUnyTgxsO/copy. To assign the Electronic Exit Ticket, share the link to the copy that you make with students (do not share the original link provided here, as that will create a new copy for each student, and you won't have access to their responses). Make sure you attend to the last two prompts in the exit ticket before next class:

- *How do you think this might be similar to or different from how energy transfers from the magnetron to the food inside the microwave oven?*
- *An earthquake is caused by unbalanced forces at a fault (boundary) between two pieces of Earth's crust. What might the unbalanced forces be causing energy transfer in the microwave oven?*

Suggest that we pick up with those questions next time, and consider how we can use the ideas we now have to understand what is happening with these types of waves we can't see.

ASSESSMENT OPPORTUNITY

What to look for/listen for in the moment: Use *L3 Electronic Exit Ticket Key* to score the first three questions (multiple choice), which ask students to engage in mathematical thinking. For the second two questions (open response), look for mechanistic explanations about how energy transfers from the magnetron to the food inside the microwave oven, but do not score them.

What to do: If students struggle to engage in algebraic thinking to respond to the first two questions, consider having them individually write out the variables in fraction form on whiteboards or paper, and try various operations between the variables to see what results. If they struggle with understanding the relationships represented by the mathematical model, you can give them the *Wavelength Reference* and use the images to help them further understand the relationships within the developed equation for wavelength. If they do not recognize the relationship between amplitude and energy transfer in the second question, spend more time going over the relationships on the poster.

Take notes on how students are thinking about energy transfer in the microwave, and use those ideas to navigate into Lesson 4.

Building toward: 3.B Use algebraic techniques to develop a mathematical model to identify and describe the relationship between frequency, wave speed, and wavelength. (SEP: 5.2, 5.3; CCC: 1.4; DCI: PS4.A.1)

3.A Plan and conduct an investigation to produce data to serve as evidence to support claims of how certain wave properties affect energy transfer in waves. (SEP: 3.2, 6.1; CCC: 5.2; DCI: PS3.A.4, PS4.A.1, PS4.B.1)

Additional Lesson 3 Teacher Guidance

SUPPORTING STUDENTS IN MAKING CONNECTIONS IN MATH	CCSS.MATH.CONTENT.HSN.Q.A.2 Define appropriate quantities for the purpose of descriptive modeling. Students use a physical manipulative to help identify where energy is stored and transferred as a wave moves across a spring. These identified quantities are then used to build a descriptive model of how energy is transferred in a wave. CCSS.MATH.CONTENT.HSA.SSE.B.3 Choose and produce an equivalent form of an expression to reveal and explain properties of the quantity represented by the expression. Students identify the mathematical relationships between frequency, cycles, time, and distance. For example, they express period as time/cycle to make sense of the inverse relationship between frequency and period. They use these relationships to develop a mathematical model that shows how an emergent property of the system (wavelength) is related to two variables: a property of the medium (wave speed) and an independent input property of the wave (frequency).