ShakeAlert
Version of activity from:

IRIS
www.iris.edu/earthquake

The Human Wave

Modeling *P* and *S* waves in the classroom

http://www.iris.edu/hq/inclass/lesson/32

Incorporated Research Institutions for Seismology (www.iris.edu/earthquake)
Activity modified with permission for ShakeAlert (www.shakealert.org).

Beginner

1 hour

Whole Class

Demo

OVERVIEW

Lined up shoulder-to-shoulder, learners are the medium that *P* and *S* waves travel through in this simple, but effective demonstration. Once "performed", the principles of *P* and *S* waves will not be easily forgotten.

This demonstration explores two of the four main ways energy propagates from the hypocenter of an earthquake as *P* and *S* seismic waves (Appendix A). In this demo, learners "experience" the waves as they line up shoulder-to-shoulder to "become" first the solid, then liquid material through which the waves travel. The physical nature of the *Human Wave* demonstration makes it a highly engaging kinesthetic learning activity that helps learners grasp, internalize and retain abstract information.

Figure 1*: A P wave traveling through the tightly bound molecules of a solid in a instructor-education workshop. Roger Groom's Mount Taber Middle School Earth-science class.*

OBJECTIVES

Learners will be able to:

1. Distinguish between *P* and *S* waves based on:
   A) speed
   B) direction of particle motion relative to wave propagation
   C) materials through which they propagate
2. Explain molecularly, why *S* waves are not able to travel in a liquid, whereas *P* waves are able to travel in a liquid
3. Explain how *P* and *S* waves provide evidence for Earth's interior

CONTEXT*

Audience

This activity could be done with most any novice geoscience learning group from late elementary through secondary or even early college. It can also work for informal education or public outreach venues as an interactive demonstration.

Pre-knowledge & learning sequence

It is best if the learners have some knowledge of earthquakes.

This lesson would benefit from a general introduction to plate tectonics.

* *Context from: https://serc.carleton.edu/ANGLE/educational_materials/activities/205335.html*

MATERIALS

- Space in the front of the room for 10-15 learners to line-up shoulder-to-shoulder
- Computer with a projection system
- Download animations of the different waves: www.iris.edu/hq/inclass/animation/seismic_wave_motions4_waves_animated
- Venn Diagram worksheet, Page SW-1; print as needed
- **OPTIONAL**: Student Worksheets pages SW-1– SW-3

INSTRUCTOR PREP

- Watch a classroom demo video of the *Human Wave* activity *www.iris.edu/hq/inclass/video/254*. In the video, time & distance are recorded and plotted on a graph. Graphing is not required in this lesson, but is described briefly in "EXTENSION" on page 4.
- Suggested supplement: Slinky© activity is a good partner to the *Human Wave*. Watch a Slinky© video demonstration here: www.iris.edu/hq/inclass/video/202
- Learners should already be familiar with:
  1) the concept that the Earth is made of layers, including solid mantle, liquid outer core, and solid inner core.
  2) characteristics of different types of seismic waves.
- Additional **Instructor Background** information is in Appendix A.

LESSON DEVELOPMENT

ACTIVITY FLOW

There are several ways to use this demo. It can precede or follow a Slinky© demonstration depending on the rest of your instruction. As written here, it follows and reinforces instruction of seismic waves with the Slinky©. An optional student worksheet activity is described in the box "EXTENSION" on page 4.

Stage 1:

1. Today we are going to have an earthquake in class!
2. Ask for approximately half the learners in the class to line up from tallest to shortest so that the student's shoulders more closely match in height.

Stage 2:

1. Tell the learners that you are the earthquake and that they are a line of molecules in a material through which seismic energy will propagate (travel) through the line.
2. Ask the line of "molecules" how they could become an elastic solid. If learners have difficulty, coach them to find the answer.

   ANSWER: The shoulder-to-shoulder line stands with their feet shoulder width apart. To model tightly packed molecules in a rigid solid, they can't slide past one another. Therefore, they need to be very close together by placing their arms over the shoulders of the person next to them, chorus-line style.

VOCABULARY

Elastic Deformation: Measure of an object's ability to change shape when a force is applied, and return to its original shape when the force is released.

***P* Wave**: This primary body wave is the fastest, thus the first seismic wave detected by seismographs. Able to move through both liquids and solid rock. Also called compressional waves, they compress and expand (oscillate) the ground back and forth in the direction of travel, similar to sound waves.

Propagation: The act or process of propagating, especially the process by which a disturbance, such as the motion of seismic waves, is transmitted through a medium such as rock, air, or water.

***S* Waves**: Shear waves that are secondary body waves that oscillate the ground perpendicular to the direction of wave travel. They travel about 1.7 times slower than *P* waves. Because liquids will not sustain shear stresses, *S* waves will not travel through liquids like water, molten rock, or the Earth's outer core. *S* waves produce vertical and horizontal motion of the ground.

Seismic Wave: an elastic wave generated by an impulse such as an earthquake or an explosion. Seismic waves may travel either through the earth's interior (*P* and *S* waves) or along or near the earth's surface (Rayleigh and Love waves). Appendix A, Table 1.

3. Remind learners that solids are also elastic. (See Vocabulary, page 2.) Ask: *What does that mean in terms of how the "molecules" should respond when a seismic wave passes through?*

ANSWER: The group should be rigid, but not overly so. Since they are an elastic material they should deform only in response to the force that they feel and return to their original position. It is important that the molecules not be too rigid (e.g. not move when bumped) nor too limp (e.g. fall into the person next to them) for the demonstration to be effective.

STAGE 3:

Seated learners will begin to fill in the Venn diagram (Page 11; SW–1) about *P* and *S* waves during the demo and discussions.

Modeling a *P* wave in a solid

1. Lightly push the shoulder of the first student so that they bump the student next to them. This causes them to move closer together temporarily, a compression, followed by spreading farther apart temporarily, a dilation. This pattern propagates down the line.
2. Ask: "*If I was the earthquake that released energy into the material, then what was transmitted? Energy? Material? Neither? Both?*" Be sure to encourage learners to provide evidence for their claim.

   ANSWER: Energy was transmitted through the solid material from one end of the line to the other end. The molecules returned to their original position and were NOT permanently deformed.
3. Ask: "*How did the molecules move as compared to the direction of the energy?*"

   ANSWER: Parallel to, or in the direction of wave propagation. Since the material is elastic, the molecules were deformed as the wave passed, but they returned to their original position.
4. Ask: "*Did it take some time for the energy to move from one end of the material to the other?*"

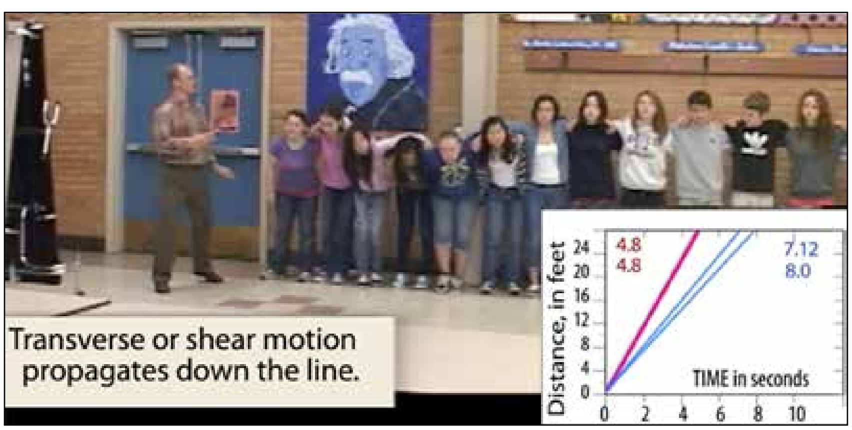


***Figure 2**: Screen grab of video of learners "performing" an S wave in a solid. Multiple P and S wave times were recorded and plotted on the graph. By timing and plotting this exercise, learners see how seismologists learned how to use the speed of seismic waves to better understand distance to epicenter. Many thanks to Roger Groom's Mount Tabor Middle School for their help with this. Watch this video at: www.iris.edu/hq/inclass/video/254*

SAFETY

Have a "spotter" at one end of the line to ensure that the last person is not bumped over.

TIP 1

Depending on the maturity of your learners, this demonstration may work best with homogeneous grouping by gender.

TIP 2

Since this is a kinesthetic demonstration, it may not be appropriate for some learners with physical disabilities to participate.

ANSWER: Yes

5. Ask: *Since it took x amount of time for the energy to move from one end of the material to the other, what does that mean about the wave?*

   ANSWER: It has a definite and measurable velocity

Modeling an S wave in a solid

1. Starting at the end of the line, place one hand in the center of the first person's back, and a second hand on their waist. Bend them forward at the waist and then push them back to vertical.
2. The molecule's resistance to shearing (e.g. arms over each other's shoulders) will cause the shearing to propagate down the line of "molecules".
3. Again note that the wave has a velocity and that this time the deformation of the molecules was perpendicular to the direction of wave propagation.
4. Many learners will note that the S wave is slower than the *P* wave though repeating the demo and having observers time the waves can emphasize this point dramatically.
   (Because the shear motion in the demonstration is more complicated than the compression. This velocity difference could be measured with a stopwatch if the *P* and the *S* demo were repeated.)
5. Ask: "*How was the S Wave different from the P wave?*"

   ANSWER: Particles moved perpendicular to the direction of wave propagation and the *S* wave was slower than the *P* wave
6. Ask: "*How was the P Wave similar to the S wave?*"

   ANSWER: They both had a definite velocity and transferred energy from on end to the other.

Modeling a *P* wave in a liquid

1. Instruct the line of "molecules" to now become a liquid. If learners have difficulty, coach them to the answer.

   ANSWER: The line should stand shoulder-to-shoulder with their feet shoulder-width apart. Molecules in a liquid can slide past one another but there is little free space between them. Therefore, the learners' shoulders should touch one another but they should no longer be linked chorus-line style (Figure 3).
2. Remind the "molecules" that they are still elastic. This means that even though they are liquids they should deform to the force that they feel and return to their original position. It is important that the molecules not be too rigid (e.g. not move when bumped) nor too limp (e.g. fall into the person next to them) for the demonstration to be effective.
3. From the tall end of the line, lightly push first student's shoulder so that they bump the student next to them. This causes them to move closer together temporarily, a compression, followed by spreading farther apart temporarily, a dilation. This pattern propagates down the line.
4. Ask: "*Was there a difference between a P wave in a liquid vs in a solid?*"

   ANSWER: There was no noticeable difference (though it should be noted that in the earth, the energy is transferred more slowly in a liquid. If time allows you might explore why this occurs with your learners.)

Modeling an S wave in a liquid

EXTENSION

To answer the question, "*Which wave is faster?*" you can provide concrete data by expanding this activity to include recording and graphing the *P*- & *S*-wave travel times.
To do that, you will need:

- Space to line up the entire class of learners shoulder to shoulder
- Stopwatch
- Student Graph. Print as needed, either Page SW-2 or Page SW-3

Watch the video, Figure 2.

Figure 3. *Modeling a P wave traveling through the molecules of a liquid. Compare with Figure 1, the S wave traveling through a solid. Larry Braille demonstrates wave during instructor workshop.*

1. Since it is a liquid, they are still standing shoulder-to-shoulder, not chorus-line style.
2. Starting at the end of the line, place one hand in the center of the first person's back, and a second hand on their waist. Bend the student forward at the waist and then back up again. This time the shear disturbance cannot propagate down the line.

   TIP - When doing this demo, the second person in line frequently bends at the waist "sympathetically". This should be anticipated and you should clarify their movement to the class by asking them, "*did you feel, or see the disturbance?*". Once clarified, the demo should be repeated so that this time they only move when they feel the disturbance.
3. Ask: "*Was there a difference between an S wave in a liquid vs. a solid? What was it?*

   ANSWER: Yes, the wave did not travel through the liquid!
3. Ask: "*Based on these demonstrations, why can't an S wave travel in a liquid?*"

   ANSWER: Because the molecules in a liquid are not rigid, they can slip past one another. As a result, sharing motion is not resisted and does not propagate.

STAGE 4:

1. Quickly reverse the learners with the remaining half of the class and repeat the demo. Each group can then both witness and experience the transfer of energy.
2. Document this second demonstration by creating a Venn (Page 11; SW-1) diagram for *P* and *S* waves on the board. Learners should also complete their version at their seats.
3. Ask: "*We have examined this model for how the line of learners can behave like seismic waves moving through Earth. Do you think it is completely accurate? How could it be different from reality?*"

   ANSWER: The Human Wave demo is a functional model. That is, it describes functions and processes by analogy, thus, it is both like and unlike the target it represents. Accept answers generated by learners but be sure to supplement these with the ideas mentioned in the instructor's background section.

STAGE 5:

1. Before the second group return to their seats, divide the learners in the following way; the first quarter of the learners should be solids, the middle half of the learners should be liquids, and the final quarter should be solids. You may have to add a few learners. (See Figure 4 for similar example.)
2. Ask learners to predict, "*What do you think will happen if a P wave were to propagate through the line? What about an S wave?*"

   ANSWER: Accept all responses as hypotheses.
3. Test their hypothesis by sending first a *P* wave, and then an *S* wave through the line. Because *P* waves propagate in both solids and liquids, the *P* wave will propagate from one end to the other. However, the *S* wave will stop when it reaches the solid/liquid boundary because liquids do not resist shearing. This final demo models the S wave shadow zone; evidence that Earth's core is a liquid.

TIP

If you have not already covered Earth's internal structure, don't mention the connection to Earth's structure yet. However, if you have already provided instruction on Earth's interior structure, a discussion connecting the demo to the S-wave shadow zone is warranted. See Appendix A for shadow-zone descriptions.

STRENGTHS AND WEAKNESSES OF THE MODEL

This demo is a simplified model of natural phenomena. As such it is especially important to emphasize both the strengths and weaknesses of the model to learners. Such an explicit discussion helps learners focus on the model as a conceptual representation rather than a concrete copy of reality.

Limitations of the model to address with learners:

- The model has scale and compositional limitations
- Seismic waves travel outward all directions; not just in one direction as does the line of learners
- Seismic waves also travel at speeds that are much faster, about 3000x faster, than the waves in the Human Wave model
- The particle motion of an S wave can be in any direction that is perpendicular to the direction of wave propagation; not just up and down as shown in the demo
- Even though kinetic theory is not the targeted learning outcome of this demonstration, instructors should be specific about pointing out that in this demo the student "particles" are stationary for the purposes of the demo, but actual particles are constantly in motion, even in a solid.

Figure 4: *Composite image from the video mentioned in Figure 2. Learners simulate a cross section of the earth by having groups be solid mantle, liquid outer core, solid inner core, etc. The P wave will be able to travel through the line, but the S wave will stop at the liquid outer core.*

APPENDIX A

Instructor background—Seismic Waves, Travel-time Curves & Shadow Zones

Seismic Waves

The energy from an earthquake radiates outwards in all directions. Because of the elastic properties of Earth's materials (i.e., rock), this energy propagates as four main types of seismic waves. Compressional or Primary (*P*) and Shear or Secondary (*S*) waves propagate through the Earth's interior and are known as body waves. Love and Rayleigh waves propagate primarily at and near the Earth's surface and are called surface waves. Table 1 (next page) summarizes characteristics of the *P*, *S,* Rayleigh, and Love waves.

Travel-time curves for distant earthquakes

Earthquakes create seismic waves that travel through the Earth with predictable arrival times for *P* and *S* waves. A travel-time curve (Figure 5) is a time vs. distance graph of the time that it takes for seismic waves to travel from the hypocenter of an earthquake to seismograph stations around the world. Student graphs of the time it takes the human wave to travel across the group will be similarly "predictable".

VIDEO RESOURCES

How do scientists know how far away the earthquake occurred? Watch this 1-min animation: www.iris.edu/hq/inclass/video/125

Learn more about Travel-time curves in a 2-minute animation: www.iris.edu/hq/inclass/animation/120

How do *P* & *S* waves give evidence for a liquid outer core? Seismic Shadow zones are described in the animation: www.iris.edu/hq/inclass/animation/121

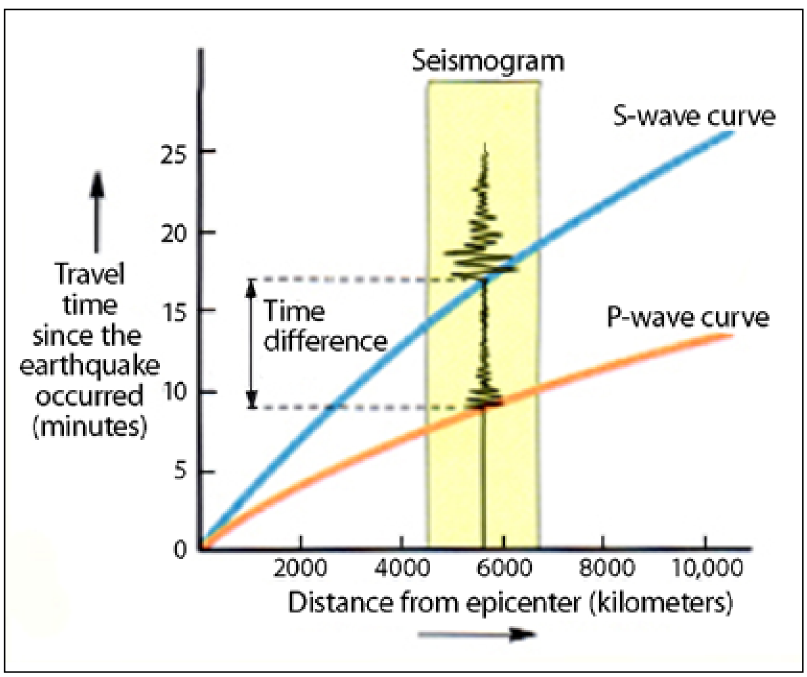
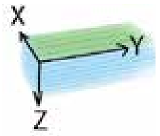
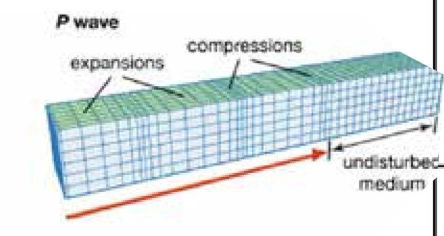


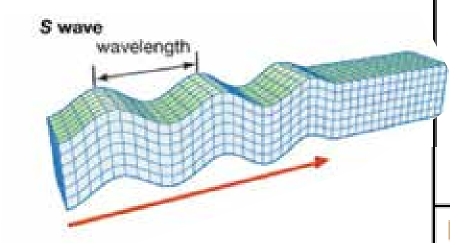
Figure 5: *Travel-time curves for a earthquake thousands of kilometers away. The amount of time between the P and S wave arrival times is predictable. In this case, the time difference is about 8 seconds, so the earthquake must be almost 6,000 kilometers. The student graphs will show similar time differences between the P and S waves.*

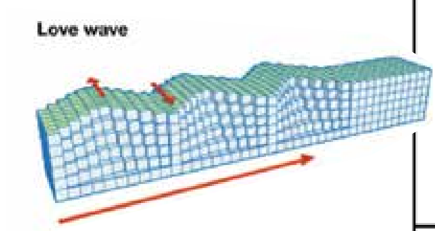
Types of seismic waves

Perspective views of seismic-wave propagation through a grid representing a volume of material. X and Y are parallel to the Earth's surface; Z direction is depth.









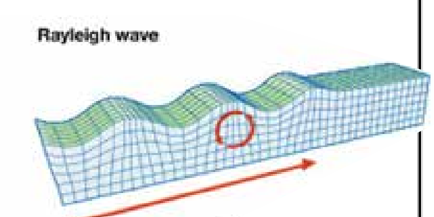


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Table 1: Seismic Waves

Wave Type (and names)	Particle Motion	Typical Velocity	Other Characteristics
P, **Compressional**, Primary, Longitudinal	Alternating compressions ("pushes") and dilations ("pulls") which are directed in the same direction as the wave is propagating (along the ray path); and therefore, perpendicular to the wavefront.	**V_P ~ 5 – 7 km/s in typical Earth's crust; >~ 8 km/s in Earth's mantle and core; ~1.5 km/s in water; ~0.3 km/s in air.**	P motion travels fastest in materials, so the P-wave is the first-arriving energy on a seismogram. Generally smaller and higher frequency than the S and Surface-waves. P waves in a liquid or gas are pressure waves, including sound waves.
S, **Shear**, Secondary, Transverse	Alternating transverse motions (perpendicular to the direction of propagation, and the ray path); commonly approximately polarized such that particle motion is in vertical or horizontal planes.	**V_S ~ 3 – 4 km/s in typical Earth's crust;** >~ 4.5 km/s in Earth's mantle; ~ 2.5-3.0 km/s in (solid) inner core.	S-waves do not travel through fluids, so do not exist in Earth's outer core (inferred to be primarily liquid iron) or in air or water or molten rock (magma). S waves travel slower than P waves in a solid and, therefore, arrive after the P wave.
L, **Love**, Surface waves	Transverse horizontal motion, perpendicular to the direction of propagation and generally parallel to the Earth's surface.	V_L ~ 2.0 - 4.4 km/s in the Earth depending on frequency of the propagating wave, and therefore the depth of penetration of the waves. In general, the Love waves travel slightly faster than the Rayleigh waves.	Love waves exist because of the Earth's surface. They are largest at the surface and decrease in amplitude with depth. Love waves are dispersive, that is, the wave velocity is dependent on frequency, generally with low frequencies propagating at higher velocity. Depth of penetration of the Love waves is also dependent on frequency, with lower frequencies penetrating to greater depth.
R, **Rayleigh**, Surface waves, Ground roll	Motion is both in the direction of propagation and perpendicular (in a vertical plane), and "phased" so that the motion is generally elliptical – either prograde or retrograde.	V_R ~ 2.0 - 4.2 km/s in the Earth depending on frequency of the propagating wave, and therefore the depth of penetration of the waves.	Rayleigh waves are also dispersive and the amplitudes generally decrease with depth in the Earth. Appearance and particle motion are similar to water waves. Depth of penetration of the Rayleigh waves is also dependent on frequency, with lower frequencies penetrating to greater depth.

Animations: www.iris.edu/hq/inclass/animation/seismic_wave_motions4_waves_animated

Seismic-wave Shadow Zones

Most of the direct evidence that we have about Earth's deep interior comes from the study of seismic waves that penetrate the Earth and are recorded on the other side. Years of studying travel times of *P* and *S* waves from earthquakes to stations at various distances indicate that *P* and *S* waves travel at different speeds through different materials. Due to differences in the properties of the material at different depths, seismic energy is refracted and travels a curving path through the Earth (see text below). From this, seismologists have been able to infer the path the seismic waves take to reach any point on Earth's surface. As illustrated in Figure 4b below, *S* waves are stopped entirely at the liquid boundary, so the most-vertical paths are quenched and do not return to the surface, thus leaving what is called a "shadow zone" at all points beyond an angular distance of 104°. *P* waves, on the other hand are bent (refracted) inward at the mantle-core boundary and continue their path through the liquid to the other side. That refraction results in a *P*-wave shadow zone at an angular distances of 104° to 140° from a given earthquake that does not receive any direct *P* waves.

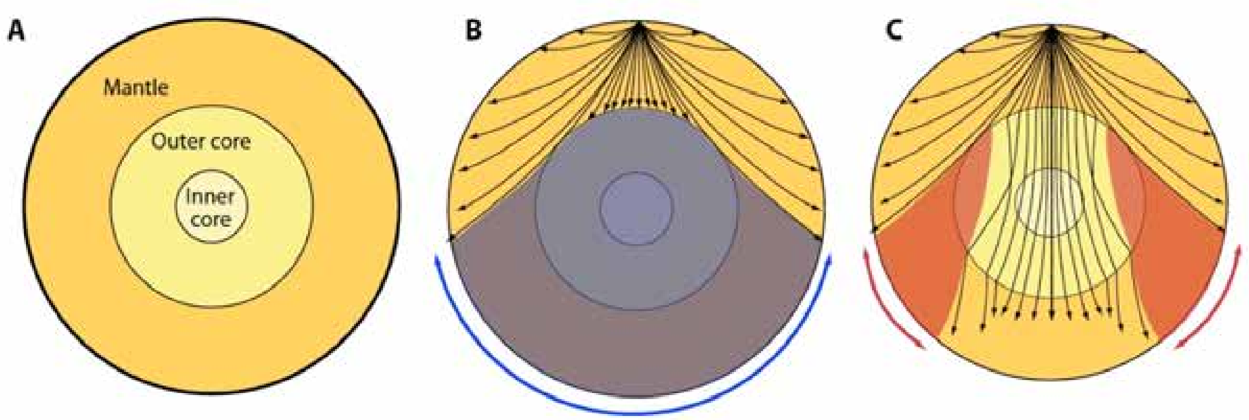

Figure 1—Simplifications of :
A) Cross section of the Earth, **B**) S-wave paths and shadow zone; and **C**) P-wave paths and shadow zone

Animations to help understand shadow zones:

- Introduction to Shadow zones: www.iris.edu/hq/inclass/animation/121
- Using light as an analogy to understand shadow zones: www.iris.edu/hq/inclass/animation/122
- Why do seismic waves travel a curving path through the Earth? www.iris.edu/hq/inclass/animation/216
- Learn more about travel time curves: www.iris.edu/hq/inclass/animation/120

Earthquake ray paths and arrival times are more complex than illustrated in the animations, because velocity in the Earth does not simply increase with depth. Velocities generally increase downward, according to Snell's Law, bending rays away from the vertical between layers on their downward journey; velocity generally decreases upward in layers, so that rays bend toward the vertical as they travel out of the Earth (See link above to learn more about why they travel a curving path.) Snell's Law also dictates that rays bend abruptly inward at the mantle/outer-core boundary (sharp velocity decrease in the liquid) and outward at the outer core/inner core boundary (sharp velocity increase).

APPENDIX B

NGSS Science Standards

Energy

- **MS-PS3-5** Construct, use, and present arguments to support the claim that when the kinetic energy of an object changes, energy is transferred to or from the object. http://ngss.nsta.org/DisplayStandard.aspx?view=pe&id=166

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Engaging in Argument from Evidence Engaging in argument from evidence in 6–8 builds on K–5 experiences and progresses to constructing a convincing argument that supports or refutes claims for either explanations or solutions about the natural and designed world(s).	**PS3.B: Conservation of Energy and Energy Transfer** When the motion energy of an object changes, there is inevitably some other change in energy at the same time.	**Energy and Matter** Energy may take different forms (e.g. energy in fields, thermal energy, energy of motion)

Waves and Their Applications in Technologies for Information Transfer:

- **HS-PS4-1** Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media. [Clarification Statement: Examples of data could include electromagnetic radiation traveling in a vacuum and glass, sound waves traveling through air and water, and seismic waves traveling through the Earth. http://ngss.nsta.org/DisplayStandard.aspx?view=pe&id=116

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
Developing and Using Models Modeling in 6–8 builds on K–5 experiences and progresses to developing, using, and revising models to describe, test, and predict more abstract phenomena and design systems.	**PS4.A: Wave Properties** 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.	**Cause and Effect** Empirical evidence is required to differentiate between cause and correlation and make claims about specific causes and effects.

Name ______________________

Date ______________________

Venn Diagram—Contrast and compare P & S waves

How are they different? Write details in the outer circles.

How are they alike? Write how they are alike where the circles overlap.

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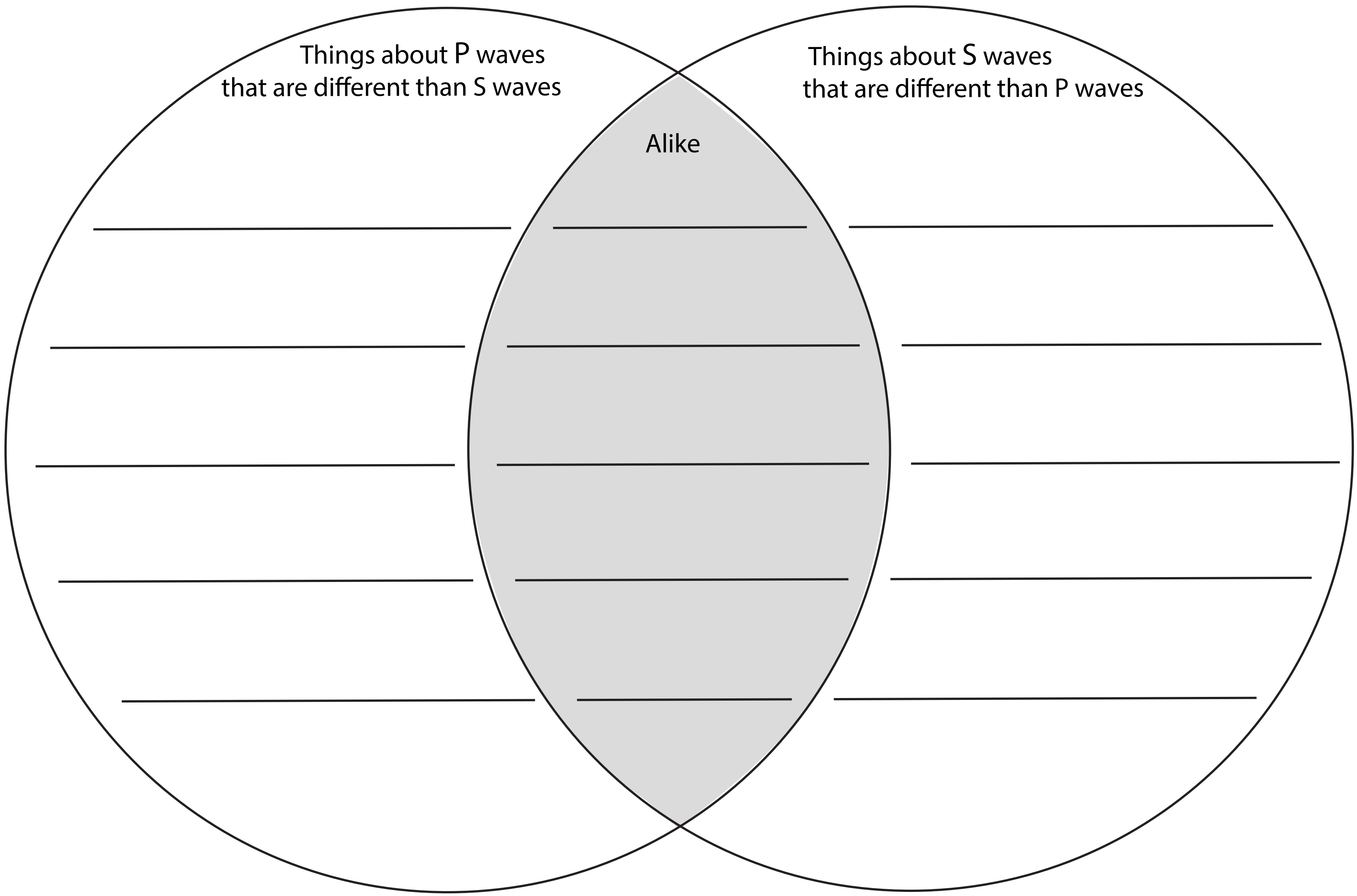

NAME: ____________________________________

DATE: ____________________________________

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PLOTTING THE HUMAN *P* & *S* WAVES THROUGH SOLIDS

TABLE OF SEISMIC-WAVE ARRIVAL TIMES THROUGH A SOLID

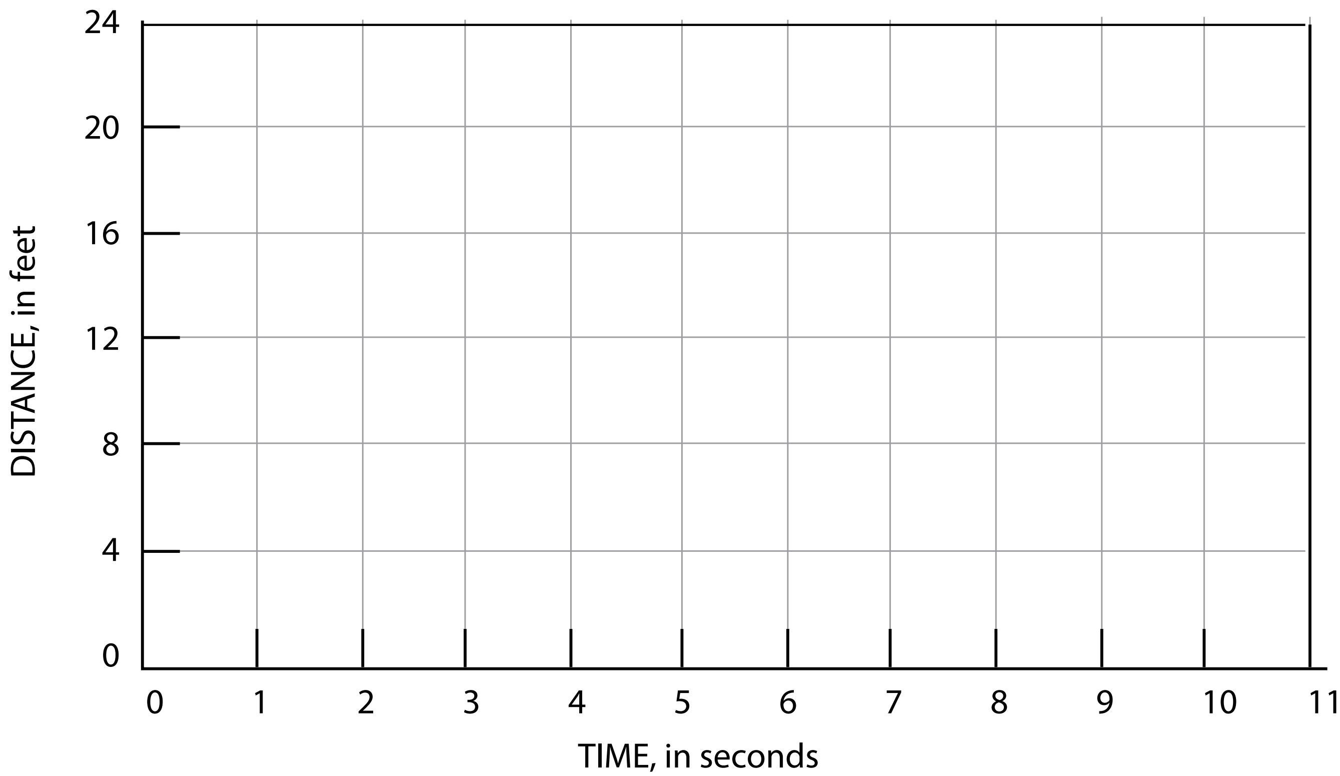
Wave type	Seconds	Wave type	Seconds
P wave #1		S wave #1	
P wave #2		S wave #2	
P wave #3		S wave #3	

Which wave is the fastest? ____________________________________

Why is it faster? ____________________________________

____

TIME vs DISTANCE GRAPH



NAME: ______________________________

DATE: ______________________________

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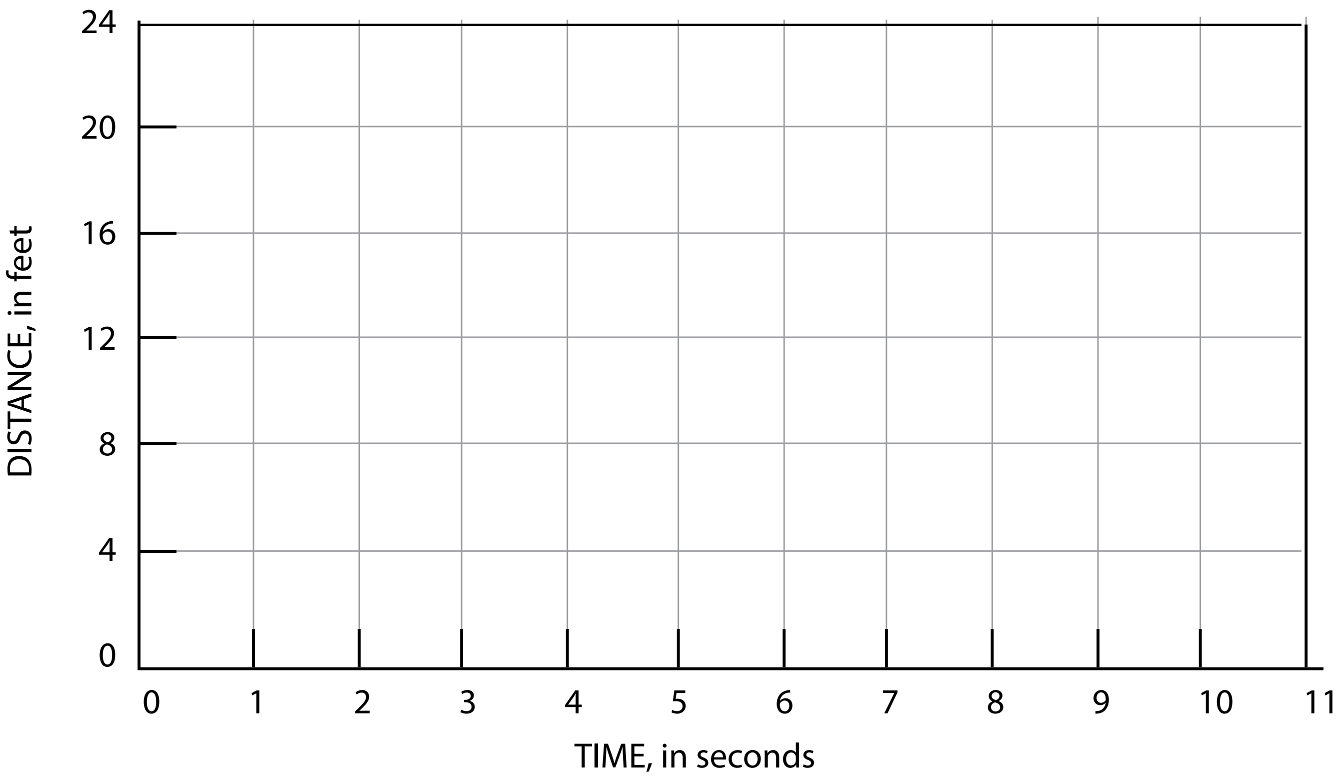
PLOTTING P & S WAVES THROUGH SOLIDS AND LIQUIDS

TABLE OF SEISMIC-WAVE ARRIVAL TIMES THROUGH LIQUIDS AND SOLIDS

	In solid	**In liquid**	**In solid-liquid-solid**
P Wave			
trial 1	_______ seconds	_______ seconds	_______ seconds
trial 2	_______ seconds	_______ seconds	_______ seconds
trial 3	_______ seconds	_______ seconds	_______ seconds
S Wave			
trial 1	_______ seconds	_______ seconds	_______ seconds
trial 2	_______ seconds	_______ seconds	_______ seconds
trial 3	_______ seconds	_______ seconds	_______ seconds

TIME vs DISTANCE GRAPH



Incorporated Research Institutions for Seismology

IRIS

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