IS5 Physics in the Universe Instructional Segment 5: Waves and Electromagnetic Radiation

At the end of IS4, students found **evidence [SEP-7]** that supported the idea that massive blocks of crust are moving, sometimes diving deep into Earth's interior. One of the main ways that we investigate Earth's interior is through seismic waves. Before students can understand that evidence, they must first understand the basic properties of waves. Instructional segment 5 introduces mathematical representations of waves and develops models of wave properties and behaviors.

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 5: WAVES AND ELECTROMAGNETIC RADIATION

Guiding Questions

- How do we know what is inside the Earth?
- Why do people get sunburned by UV light?
- How do can we transmit information over wires and wirelessly?

Performance Expectations

Students who demonstrate understanding can do the following:

HS-ESS2-1. Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features. [Clarification Statement: Emphasis is on how the appearance of land features (such as mountains, valleys, and plateaus) and sea-floor features (such as trenches, ridges, and seamounts) are a result of both constructive forces (such as volcanism, tectonic uplift, and orogeny) and destructive mechanisms (such as weathering, mass wasting, and coastal erosion).] *[Assessment Boundary: Assessment does not include memorization of the details of the formation of specific geographic features of Earth's surface.]* (Introduced in IS4)

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.] *[Assessment Boundary: Assessment is limited to algebraic relationships and describing those relationships qualitatively.]*

HS-PS4-2. Evaluate questions about the advantages of using a digital transmission and storage of information. [Clarification Statement: Examples of advantages could include that digital information is stable because it can be stored reliably in computer memory, transferred easily, and copied and shared rapidly. Disadvantages could include issues of easy deletion, security, and theft.]

HS-PS4-3. Evaluate the claims, evidence, and reasoning behind the idea that electromagnetic radiation can be described either by a wave model or a particle model, and that for some situations one model is more useful than the other. [Clarification Statement: Emphasis is on how the experimental evidence supports the claim and how a theory is generally modified in light of

PHYSICS IN THE UNIVERSE INSTRUCTIONAL SEGMENT 5: WAVES AND ELECTROMAGNETIC RADIATION

new evidence. Examples of a phenomenon could include resonance, interference, diffraction, and photoelectric effect.] *[Assessment Boundary: Assessment does not include using quantum theory.]*

HS-PS4-4. Evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter. [Clarification Statement: Emphasis is on the idea that photons associated with different frequencies of light have different energies, and the damage to living tissue from electromagnetic radiation depends on the energy of the radiation. Examples of published materials could include trade books, magazines, web resources, videos, and other passages that may reflect bias.] *[Assessment Boundary: Assessment is limited to qualitative descriptions.]*

HS-PS4-5. Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy [Clarification Statement: Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology.] *[Assessment Boundary: Assessments are limited to qualitative information. Assessments do not include band theory.]*

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a practice or disciplinary core idea.

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-1] Asking Questions and Defining Problems [SEP-2] Developing and Using Models [SEP-5] Using Mathematics and Computational Thinking [SEP-7] Engaging in Argument from Evidence [SEP-8] Obtaining, Evaluating, and Communicating Information	ESS2.A: Earth Materials and Systems ESS2.B: Plate Tectonics and Large-Scale System Interactions PS3.D: Energy in Chemical Reactions PS4.A: Wave Properties PS4.B: Electromagnetic Radiation PS4.C: Information Technologies and Instrumentation	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-4] Systems and System Models [CCC-7] Stability and Change

CA CCSS Math Connections: A-SSE.1a–b, 3a–c; A-CDE.4; N-Q.1–3; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.9–10.8; RST.11–12.1, 7, 8; WHST.9–12.2.a–e, 8

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

Ask students if they have ever experienced a thunderstorm approaching. Students may be familiar with the idea that when they see a lightning bolt, they can figure out how far away it was by counting the time until they hear a clap of thunder. How does this work? Both the light from lightning and sound from thunder are dramatic forms of energy that travel away from the storm cloud. In this instructional segment, students will **explain [SEP-6]** how energy moves as waves through materials and the factors that affect the speed of those waves.

Students started developing models of wave amplitude and wavelength in grade four (4-PS4-1A) and extended those models to include simple mathematical representations of waves in the middle grades (MS-PS4-1). Now, students extend this model further to include **mathematical representations [SEP-5]** of waves, including relationships involving their speed and frequency.

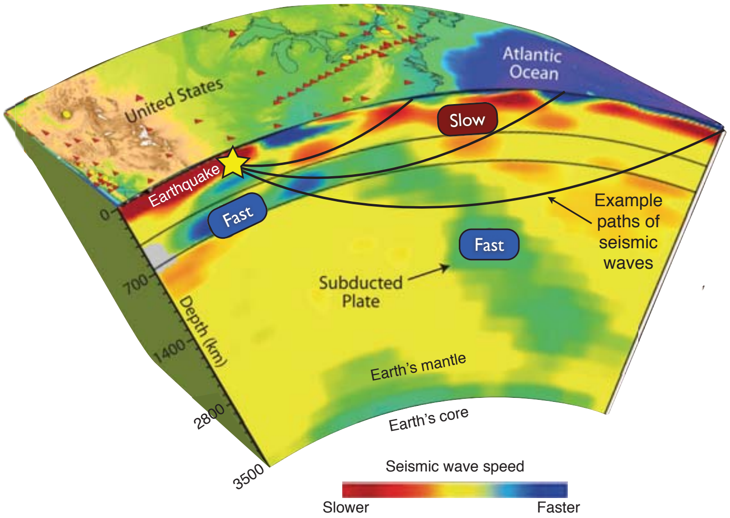
At the high school level, students can describe a wave as a disturbance or oscillation that transmits energy without transmitting matter. Mechanical waves travel through a medium, temporarily deforming the material. Restoring forces caused by elastic properties in the medium then reverse this deformation. For example, sound waves in the atmosphere propagate when molecules in the air hit neighboring particles and then recoil to their original condition. These collisions prevent particles from traveling in the direction of the wave, ensuring that energy is transmitted without the movement of matter. The second type of wave, electromagnetic, does not require a medium for transmission.

The medium that waves travel through has a huge impact on the speed at which the **energy [CCC-5]** travels. Even though electromagnetic waves can travel through space without a medium, their speed is also affected when they are travelling through a medium. Electromagnetic waves are temporarily absorbed and re-emitted by atoms when they flow through a medium, a process that slows the wave down depending on the composition and density of the atoms in the medium. Light travels through a diamond at less than half the speed that it travels through empty space. For mechanical waves, the speed dependence is more intuitive because the strength of the restoring force that allows waves to propagate through a medium depends on the stiffness of the material and its density. Stiffer materials will pop back into place faster and therefore move energy more quickly.

Students extend the **mathematical [SEP-5]** representation of waves they made in the middle grades (MS-PS4-1) to include the velocity of waves. Students must understand frequency, wavelength, and speed of waves, and understand the relationship between them (HS-PS4-1). For example, students should be able to evaluate the claim that doubling the frequency of a wave is accomplished by halving its wavelength. To evaluate such claims, students should be able to construct basic mathematical models of waves such as $v = f\lambda$ (where v = wave velocity, f = frequency, and λ=wavelength), given that $f = 1/T$ (where T = the period of the wave). Students should be able to solve for frequency, wavelength, or velocity given any of the other two variables. It is important that students realize that the equation for periodic waves is applicable to both mechanical and electromagnetic waves in a variety of media.

Seismologists can measure the amount of time it takes seismic waves to travel different distances to map out the properties of materials in Earth's interior. In an earthquake, seismic waves spread out in all directions (see snapshot 7.12 on geometric spreading in IS2) and can be recorded all over the globe. As the waves travel through denser material, they speed up and arrive sooner. These arrival time variations can be combined for thousands of earthquakes recorded at hundreds of stations around the globe to map out the materials in Earth's interior. These *seismic tomography* maps provide evidence for plate tectonics as they reveal dense plates sinking down into the mantle. At the end of IS4, students **interpreted data [SEP-4]** from radiometric dating to discover that there is no seafloor older than 280 million years and then **asked questions [SEP-1]** about where it could have gone. With seismic tomography, they can gather **evidence [SEP-7]** that answers this question—it is sinking into Earth's interior (figure 7.55).

Figure 7.55. Seismic Tomography Reveals Evidence of Plate Tectonics



Seismic waves move more quickly or more slowly as they move through different materials. Seismologists use this fact to map out the structure of Earth's interior. This image reveals evidence of plate tectonics and California's geologic history. The remnants of a large plate sinking beneath North America is believed to be the Farallon Plate that used to subduct off the coast of California (a process that created the massive granitic rocks of the Sierra Nevada). *Source*: van der Lee and Grand n.d.

Seismic waves can also reveal information about the state of matter because they behave differently in liquids than they do in solids. Liquids flow because there is very little resistance when molecules try to slide past one another. When seismic waves involve oscillations with a sliding motion (such as transverse or shear waves called S-waves, whose oscillations are perpendicular to their direction of travel), liquids do not have a force that restores the particles back to their original position and so S-waves cannot move through liquids. However, liquids do have strong resistance to compression; therefore waves that move by compression and rarefaction continue to travel through liquids. When an earthquake occurs on one side of the planet, the shaking should be recorded everywhere on the planet as the waves travel through the Earth. Stations on the exact opposite side of the Earth from an earthquake, however, do not record S-waves. This S-wave shadow is evidence that there must be a small liquid layer within Earth's core that blocks the flow of S-waves. This liquid layer of the outer core is essential for creating Earth's magnetic field (see IS3). A pioneering female seismologist named Inge Lehmann used much more complicated evidence from seismic waves to infer the existence of yet another layer, the Earth's inner core in 1936. While it sounds like a long time ago, Galileo discovered the first distant moons of Jupiter back in 1610, more than 300 years before anyone had the first clues about what lies in the very center of our own planet. Earth science is a young science in many ways.

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

Performance Expectations

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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.] *[Assessment Boundary: Assessment is limited to algebraic relationships and describing those relationships qualitatively.]*

HS-PS4-2. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity. [Clarification Statement: Examples of advantages could include that digital information is stable because it can be stored reliably in computer memory, transferred easily, and copied and shared rapidly. Disadvantages could include issues of easy deletion, security, and theft.]

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

HS-PS4-5 Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy.* [Clarification Statement: Examples could include solar cells capturing light and converting it to electricity; medical imaging; and communications technology.] *[Assessment Boundary: Assessments are limited to qualitative information. Assessments do not include band theory.]*

HS-ESS2-1. Develop a model to illustrate how Earth's internal and surface processes operate at different spatial and temporal scales to form continental and ocean-floor features.[Clarification Statement: Emphasis is on how the appearance of land features (such as mountains, valleys, and plateaus) and sea-floor features (such as trenches, ridges, and seamounts) are a result of both constructive forces (such as volcanism, tectonic uplift, and orogeny) and destructive mechanisms (such as weathering, mass wasting, and coastal erosion).] *[Assessment Boundary: Assessment does not include memorization of the details of the formation of specific geographic features of Earth's surface.]*

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[SEP-1] Asking Questions and Defining Problems [SEP-2] Developing and Using Models [SEP-5] Using Mathematics and Computational Thinking [SEP-8] Obtaining, Evaluating, and Communicating Information	PS3.D: Energy in Chemical Processes PS4.A: Wave Properties PS4.B: Electromagnetic Radiation PS4.C: Information Technologies and Instrumentation ESS2.A: Earth Materials and Systems ESS2.B: Plate Tectonics	[CCC-2] Cause and Effect: Mechanism and Explanation [CCC-7] Stability and Change

CA CCSS Math Connections: F-BF.1; N-Q.1–3; G-CO.1, 12; G-C.5; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.4; RST.9–10.8; RST.11–12.1, 7, 8

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

PHYSICS IN THE UNIVERSE VIGNETTE 7.3: SEISMIC WAVES

Introduction

Seismologists are scientists that study the Earth using a detailed, quantitative understanding of wave propagation; they are the embodiment of integrating physical science and Earth science disciplines. This vignette illustrates a lesson sequence that was used to begin an instructional segment on waves in the physical universe course. Students learned Earth and space science and physical science and PS DCIs in tandem, with an understanding of each enhancing the understanding of the other.

Day 1: Observing Earthquakes

Students observe recordings of seismic waves and relate them to what earthquakes feel like.

Days 2–3: Earthquake Early-Warning Systems: Longitudinal and Shear Waves in the Earth

Students model earthquake waves in a flexible helical spring and with their bodies to show how they could design an earthquake early-warning system.

Day 4: Digital Versus Analog Seismic Information

Students try to encode seismic information using analog and digital methods, finding that the digital method works better.

Day 5: Damage to Structures: Frequency, Wavelength, and Resonance

Students make a model of a city and see how different height buildings respond to different frequency shaking.

Days 6–7: Probing Earth’s Interior: Wave Velocity

Students measure the velocity of waves on a spring. They discover the relationship between wave speed and material properties.

Day 8: Probing Earth’s Interior II: Seismic Tomography

Students use measurements of seismic wave velocities to make maps of materials within Earth’s interior.

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Day 1: Observing Earthquakes

Anchoring phenomenon: A person feels two pulses of shaking in an earthquake with the second one bigger than the first.

The first day of the lesson, Mr. J wanted to get students to realize that earthquake shaking is energy moving in waves, and that wave energy takes time to travel through the Earth just like waves take time to travel towards the beach at the ocean. He wanted students to discover these ideas for themselves and had designed a data-rich, inquiry-based lesson. He recognized this lesson would take much more time than just providing them the answer, but he knew they would have more aha moments if they figured it out themselves. Mr. J asked students if anyone had ever felt an earthquake. A few students raised their hands and he asked them

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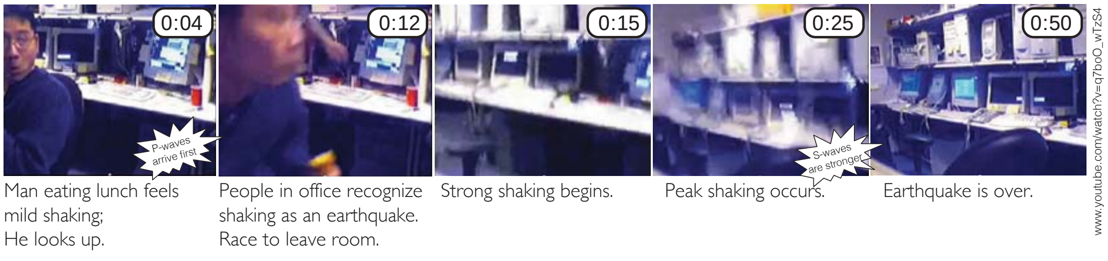
to describe what they felt, and to specifically show him with their hands the direction that their body moved during the earthquake. Some students moved their hands side to side and some shook them up and down. Mr. J emphasized the differences but highlighted that one thing everyone shared in common was that the motion repeated back and forth many times, which meant that they could describe the motion with waves. He began to build a definition of waves that they would add to throughout the next few days as they learned new things. Mr. J showed a short video clip of a Web camera that happened to be recording during an earthquake while a man was sitting and eating his lunch. He reacted to gentle shaking at the beginning of the earthquake several seconds before strong shaking begins (fig. 7.56).

Figure 7.56: Video Clip of a Person Experiencing an Earthquake



Man eating lunch feels mild shaking; He looks up.

People in office recognize shaking as an earthquake. Race to leave room.

Strong shaking begins.

Peak shaking occurs.

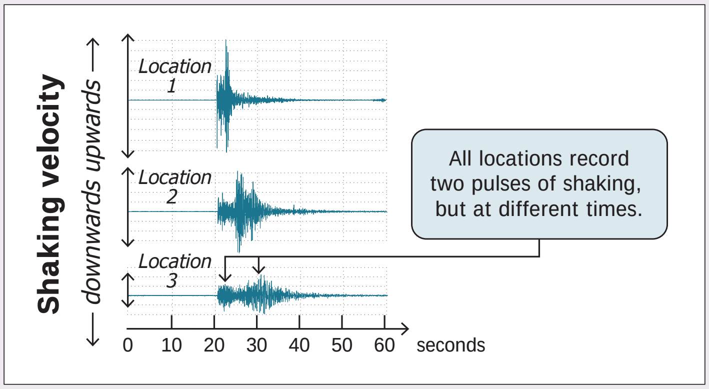
Earthquake is over.

Source: d'Alessio and Horey 2013

Investigative phenomenon: In recordings of the same earthquake at different locations around a city, all locations record two pulses of shaking but at different times.

Mr. J wondered if this were always true, and told students that sensitive seismic recording devices measured shaking at different locations all around their city. He passed out papers with measurements of a single earthquake from different locations (figure 7.57).

Figure 7.57: Measurements of an Earthquake from Different Locations



All locations record two pulses of shaking, but at different times.

Diagram by M. d'Alessio

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Mr. J made sure that students understood the axes and what the graph represented (how fast the earth was moving and in which direction over the course of an entire minute). Each student received the recording from a different location, but all students recognized that each location felt two pulses of shaking. Sally **asked [SEP-1]** if maybe there were two earthquakes, one big and one small but just a few seconds apart. Mr. J agreed that this was a good idea to consider and asked her how many seconds apart the two pulses were on her recording (**scale, proportion, and quantity [CCC-3]**). “The second one happened about 10 seconds after the first,” she said. Mr. J asked if other students also had the second pulse 10 seconds after the first and they found that every student seemed to have a different time between pulses even though they were all recording the same earthquake on the same day. Why? Students compared seismograms and noticed that the amplitude of the shaking was different. Evan **asked [SEP-1]** Mr. J if stations with stronger amplitude shaking were closer to the earthquake source, and Mr. J confirmed that this is, in general, true. He asked the students to see if there was any systematic relationship between the time difference between the pulses and how far the sensor was away from the earthquake source. Students used their phones to enter the amplitude and arrival time of the two pulses from their assigned location into a collaborative spreadsheet that Mr. J had already set up. It instantly graphed the relationship and students could see that the farther away a station was from the earthquake source, the further apart the two pulses were.

Investigative phenomenon: The farther an earthquake is away from the earthquake’s source, the more time elapses between the first and second pulse of shaking.

Mr. J then had two student volunteers act out the famous fable of a race between the tortoise and the hare as he narrated. Seismic waves, however, never take a nap like the hare in that story. For homework, Mr. J assigned students to create a visual infographic **communicating [SEP-8]** an **explanation [SEP-6]** why the two pulses of energy arrived at different times at different locations (figure 7.58). Their examples showed that the two waves traveled at different speeds.

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Figure 7.58: The Tortoise and the Hare Analogy for Two Waves Traveling at Different Speeds

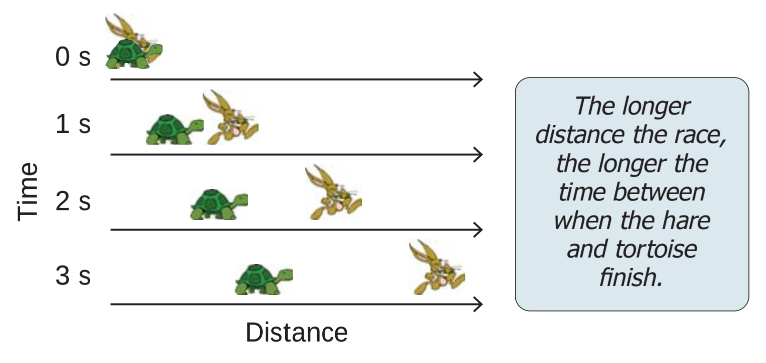

Diagram by M. d'Alessio

Days 2–3: Earthquake Early-Warning Systems: Longitudinal and Shear Waves in the Earth

In an earthquake, people can certainly feel seismic waves moving back and forth and at the ocean they can see the surf moving towards the beach. Do these two observations relate to the same type of phenomenon? Mr. J gave a short interactive lecture about mechanical waves, adding to the definition of waves the class had started on the first day. Waves are caused when a disturbance pushes or pulls a material in one direction, and a restoring force pops the material back to its original position. It is hard to make waves in clay because it does not pop back to its original position, but a material like rubber pops back instantly. Because every action has an equal and opposite reaction, the restoring force results in a new disturbance in the adjacent material. Energy gets transferred throughout the material by a cascade of actions and reactions. Waves travel well across a swimming pool or a pond because water always wants to flow back to its original flat shape (driven by gravity). The idea that the material a wave travels through affects its ability to travel is crucial to understanding seismic waves, and Mr. J foreshadowed that they would discuss the topic a lot more in a few days.

Mr. J demonstrated waves using a physical **model [SEP-2]**, a toy spring stretched out across the room. He asked students why he had chosen a spring for the demo instead of a piece of rope and students quickly identified that the spring would easily want to pop back into position. He showed how disturbing the spring by pulling it in different directions causes waves to travel down the spring differently, illustrating the difference between longitudinal and shear waves (see IRIS, Seismic Slinky at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link57). The waves went by very quickly on the spring, so Mr. J had students stand up and use their bodies as a physical **model [SEP-2]** that represent the links of a slinky to act out the particle motion of the different types of waves (see IRIS, Human Wave Demonstration at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link58).

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Mr. J wanted to relate these two types of waves to the seismic recordings from day 1. He distributed the recordings again and asked students to look more carefully at the two pulses. How were they similar and how were they different? Students offered observations from their own seismograms, including Jorge's comment that the second pulse was stronger than the first. Like the previous day, Mr. J wanted to see if there were consistent **patterns [CCC-1]** across all the seismograms. He had them measure the amplitude of the two pulses and submit their results to an online form using their smartphones. The class instantly **analyzed [SEP-4]** the results from a graph projected on the screen and determined that almost all the locations experienced stronger shaking during the second pulse. Why would that be?

Investigative phenomenon: Earthquakes release energy as two types of waves that leave the source at the same time, and the second pulse is usually stronger.

Now that Mr. J had made the students curious, he gave a mini-lecture: Much like a storm cloud simultaneously produces lightning and thunder, earthquake waves release energy as two types of waves. As the blocks of crust slide past one another, the Earth is disturbed in different directions. Textbooks and scientists refer to these motions as P-waves and S-waves, and they carry different amounts of energy moving at different speeds. P-waves are longitudinal waves caused by the sudden pushing or pulling of one section of rock against another. Because rocks are very rigid, energy from pushes and pulls like P-waves is quickly transmitted from one section of rock to the next. Although P-waves arrive quickly, earthquakes release relatively little energy as pushes or pulls, P-waves do not do much damage even in large earthquakes. Earthquakes mostly involve the sliding of two blocks of crust past one another, so they release most of their energy in the side-to-side motion of shear waves, or S-waves. That means that S-waves carry the powerful punch that causes great earthquake damage. That punch arrives seconds after the P-wave because rock is weaker in shear than for pushing/pulling, meaning that S-wave energy is not transmitted as rapidly through the material. This might be similar to your experience watching a distant lightning storm—you see lightning several seconds before booming thunder reaches you and rattles your windows.

Students would explore wave speed more in a few days, but at this point Mr. J told them that they needed to remember two basic facts: P-waves travel more quickly than S-waves and S-waves carry more energy when they finally do arrive. The fact that every earthquake comes with its own gentle warning (a P-wave) has allowed scientists and engineers to develop systems to provide cities with advance warning of strong shaking. Mr. J showed students a short video clip about earthquake early-warning systems. The video described how automated sensors near the source of an earthquake can send warning to distant locations. Even though seismic waves travel faster than the fastest fighter jets (upwards of 6 km/s, or 13,000 mph), digital signals travel through wires and airwaves near the speed of light and can therefore provide seconds to minutes of warning prior to the arrival of strong shaking. Mr. J took the

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class outside to the sports field and has them use their bodies as a physical **model [SEP-2]** of slow P-waves and fast S-waves in a kinesthetic activity that illustrated early warning (d'Alessio and Horey 2013). Japan, Mexico, and a few other locations have early-warning systems in place that send signals to schools, businesses, and millions of individual people via mobile phone and other media. California is developing its own early-warning system. For homework, Mr. J assigned students to watch a few short videos of early warning in action during earthquakes in Japan and Mexico and assigned students to write a reflection essay about what they would do with a few seconds of warning before an earthquake arrived.

Day 4: Digital Versus Analog Seismic Information

Investigative phenomenon: How can we reliably transmit shaking information from a seismic recording station to a central data processing facility?

Earthquake early warning works because information from seismic recording stations in many different locations can send their measurements to a central data processing facility instantly. To avoid costly false alarms or failing to issue a warning about a damaging earthquake, the information must be transmitted reliably. Mr. J told students that they would develop a technique for transmitting the shaking history shown by their seismogram to students on the other side of the room using a small desk lamp with a dimmer attached to it. In middle grades, students obtained information about the difference between analog and digital information transmission (MS-PS4-3). In this lesson students compared the two (HS-PS4-2). Half of the teams transmitted the information using analog techniques (adjusting the intensity of the light using the dimmer switch in order to represent the amplitude of shaking), and half came up with a digital encoding system (such as using Morse code or binary encoding to indicate amplitude values at fixed time intervals or listing frequency, amplitude, and duration values as an individual blinks to be counted). Teams summarized their encoding protocol before beginning transmission so that everyone knew how to interpret the signals from the light. Without seeing the original seismogram, the team on the other side of the room had to draw what they thought the seismogram looked like based on the signal transmitted to them and the agreed-upon protocol. Students receiving the analog signal had trouble representing the shape of the signal as the solutions drawn by different students varied dramatically. Mr. J then asked what would have happened if he had given students a seismogram with an amplitude just one tenth as strong as the one that they had. With the analog signal, the light would have gotten very dim and it would have been hard for students or even a computer light sensor to detect the slight variations in the light that represent the weaker shaking. The digital signal, however, just reported smaller amplitude numbers. Digital seismic recording devices can transmit information about weak signals and strong signals whereas analog seismic recordings are only useful within a certain amplitude range. Since

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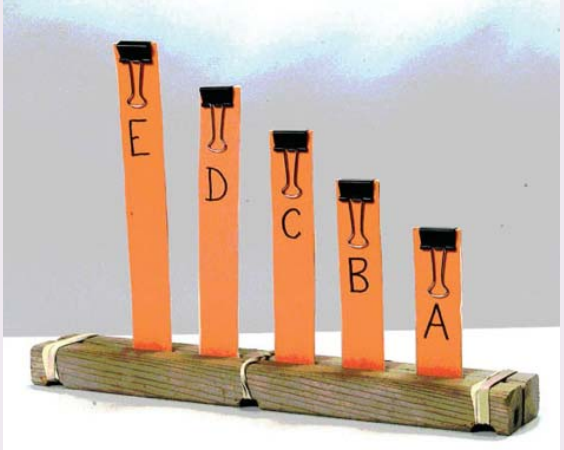
earthquakes with magnitude 5 and 8 could both cause damage yet have amplitudes that differ by a factor of 1000, digital encoding is the best strategy for transmitting seismic waves. And since the information is already encoded digitally, it is easy for a computer to process it and issue an earthquake early warning if it looks like the earthquake is large enough.

Day 5: Damage to Structures: Frequency, Wavelength, and Resonance

Investigative phenomenon: Different height buildings vibrate and deform differently even when they experience the same earthquake shaking.

Mr. J started the class off by showing a video of a life-size apartment building being tested on a gigantic shake table (World's largest earthquake test, http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link59). Is a seven-story apartment building safer or less safe than a one-story house? How about a 100-story skyscraper? Mr. J. told students that they were going to simulate buildings using a much simpler physical **model [SEP-2]**. They would model a city using different length rectangles of heavy paper to represent different height buildings (see IRIS, "Demonstrating building resonance using the simplified BOSS model" at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link60). They attached the rectangles to a ruler that represented the ground and attached a paperclip to the top of each building to represent air conditioners and other heavy objects on the buildings' roofs (figure 7.59).

Figure 7.59. Physical Model of Different Height Buildings in a City



Source: IRIS 2014

Mr. J then asked students which building they would rather live in during an earthquake. Different students had different ideas, so he invited everyone to shake their city. Sammy was very aggressive and shook her city back and forth very quickly and was amazed to see that

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the shortest building started moving more than the others. Roland shook more slowly and saw the opposite effect with the tallest building moving more than the others. This allowed Mr. J to add to the class definition of waves, adding that waves can be described by the frequency at which they move back and forth. Mr. J asked the students to describe their shaking using the words frequency and amplitude instead of just saying quickly or slowly. He asked students to do a more controlled experiment in which they shook with a constant amplitude (distance their hand moved back and forth), but changed the frequency of shaking (how quickly their hands moved from one extreme to the other) from a low frequency to a high frequency and watched what happened to the buildings. He then asked them a series of questions:

Mr. J's Question	**Answers by his students**
What did you observe during the demo?	All the buildings shook, but different buildings at different frequencies.
How did this compare to your prediction?	Different—I predicted that building X would shake the most, while the physical model showed that all buildings responded at one point or another.
Was there a **pattern [CCC-1]** in the shaking of the buildings?	Yes, first the tallest progressing to the smallest.
What controlled which buildings shook?	Students resorted to using terms like how fast, how quickly, or how much they moved their hand during the demo. Mr. J guided students to understand that the amplitude of the shaking was constant with only the frequency changing.
Therefore, if the frequency of shaking is important can anyone propose a relationship between frequency of shaking and building height?	Tall buildings shake the most at low frequencies while shorter buildings respond at high frequencies.
Let's revisit our original question. Are any of these buildings more or less likely to be damaged or collapse during an earthquake?	It depends on the frequency of the seismic waves. All of them could be at risk, depending on the frequency.

Mr. J returned again to the class definition of waves, adding that they have a characteristic wavelength. For waves in the ocean, the wavelength is easy to visualize as the distance between two wave troughs. The buildings in the physical **model [SEP-2]** shook the most

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when their height matched the wavelength of the waves, a phenomenon called resonance. Mr. J provided a short lecture with demos using a string to visualize resonance in standing waves. He then presented a **mathematical [SEP-5]** basis for the behavior of the physical model, the equation *speed = frequency x wavelength*. The students performed some simple calculations to ensure that they could plug numbers in and handle the units of this equation (HS-PS4-1).

Mr. J had heard stories of people looking out over a valley during a large earthquake and literally seeing the earth ripple as waves passed through. He wanted to know if this was reasonable. What would seismic waves look like? At the beach, ocean waves might have crests that are 30 feet (ft) apart (wavelength = 30 ft). What about seismic waves? Students return to their adopted seismic recording and look more carefully at the shaking. Mr. J asked students to calculate the frequency of the seismic waves during the earliest shaking. They might have found frequencies in the range of 1-10 Hz. Scientists can calculate the velocity of seismic waves from experiments as simple as pounding a sledge hammer against the ground and measuring how long it takes the vibrations to reach a sensor a fixed distance away. The fastest waves travel in Earth's crust is about 6,000 m/s (about 13,000 miles per hour). Knowing these two values, students calculated the wavelength. Looking across a valley a bit more than a mile across, you might be able to see two crests of a wave with 600 m wavelength, so it is possible to see but the waves would be much broader than most ocean waves at the beach.

Investigative phenomenon: Students measure the velocity and wavelength of waves from computer visualizations of seismic waves.

Mr. J next showed video clips with the results of computer simulations of famous California earthquakes (see USGS, Computer Simulations of Earthquakes for Teachers at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link61). Making detailed measurements from the computer screen, students calculated two estimates of the wave velocities: one from the distance the wave fronts traveled divided by time, and one plugging frequency and wavelength observations into the equation above. Students verified that they got the same result from each equation. They then compared these computer models to a video that visualized ripples as they were recorded by a very sophisticated network of seismic sensors during a much smaller earthquake (see American Geophysical Union, Watch the ground ripple in Long Beach, http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link62). Students discovered that the velocity was quite similar in the two cases, but that the frequency and wavelength differed for different size earthquakes. This motivated the next activity relating seismic wave velocities to the properties of the materials.

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Days 6–7: Probing Earth's Interior I: Wave Velocity

Everyday phenomenon: It hurts more to fall on solid rock than it does to fall on sand.

Mr. J started class with a rock and a bucket of sand on the table and asked students whether they thought seismic waves could travel through either of them. Most students answered no because they did not think that either one would pop back into place like a spring. He asked them if the two different materials responded to force differently, or would it hurt the same amount if you fell on the solid rock versus the soft sand? Mr. J told them that by the end of the day, he hoped they would understand some of the differences between the materials.

Investigative phenomenon: The speed of waves moving on a toy spring depends on how tightly the spring is pulled.

Mr. J returned to the physical **model [SEP-2]** of the toy spring and illustrated with a few more example earthquakes. He showed gentle disturbances and big disturbances (changing amplitude) and changed the amount of stretch in the spring by pulling it more or less before he caused the next earthquake. Students could not visually see any consistent **patterns [CCC-1]** because the spring moved so quickly, but a student recorded a video of the demonstration. Groups downloaded the video and opened it in free video analysis software (see D. Brown, Tracker video analysis and modeling tool from 2015 at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link63) so that they could watch it in slow motion and measure and compare the speed of the waves in several sample earthquakes. When students **analyzed the data [SEP-4]**, they found that the speed the waves traveled was **proportional [CCC-3]** to the length of the spring as it was stretched out more or less. Students were surprised to see that the amplitude of the disturbance didn't make much difference to the wave speed. Mr. J ended class by having students write an **explanation [SEP-6]** describing the factors affecting wave speeds, giving them a sentence starter "The speed waves travel along a spring depends on _______."

In class the next day, Mr. J returned to the bucket of sand and the rock on the table. He asked students to work in pairs to draw a diagram that showed how the investigation of the loose versus stretched spring might be a good **model [SEP-2]** for the way seismic waves might travel differently through the two materials. Olivia and Martin made the connection to restoring forces: "The restoring force is very strong in a stretched spring. Solid rock is really hard, so maybe it is like a really tight spring." Mr. J validated their idea, explaining that it may be difficult to imagine that solid rock can act like a spring that compresses and stretches, but if you pull it hard enough it actually will do just that. Earthquakes represent massive forces from huge blocks of the Earth's crust applying forces of an unimaginable **scale [CCC-3]**, and their sudden movements are strong enough to bend the rock like fingers temporarily bend the

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spring. In his honors class, Mr. J had students calculate wave speeds using equations that included the density and elastic modulus of the materials.

Investigative phenomenon: Waves change speed and wavelength when they move through materials with different properties.

Mr. J had students open up a free computer simulation to **investigate [SEP-3]** waves moving through a medium (see Falstad Ripple Tank at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link64). The simulator **models [SEP-2]** the behaviors of all types of waves. While the class was thinking of them as seismic waves, they could be water, sound, or light waves. Working in groups, students had a full 10 minutes to explore the program by selecting some of the preset scenarios in the program and adjusting settings. Each team presented the coolest picture they made and **communicated [SEP-8]** their understanding of what it showed about wave behavior. Mr. J walked around interacting with each group, encouraging them to **ask questions [SEP-1]** about what would happen and then try things out. After each group shared, Mr. J drew attention to Esmerelda and Dima's scenario, which showed what happened when waves traveled through materials with different velocities (figure 7.60). "This picture could be a slice through the Earth with different earth materials like sand on top of rock," said Mr. J. The waves leaving the source near the top left had to travel through both materials to reach the bottom right. He pointed out how the wavelength of the source was different as the waves traveled through the two materials, and asked students to estimate which material had a faster wave velocity (HS-PS4-1).

Figure 7.60. Computer Model of Waves Traveling through Materials with Different Velocities

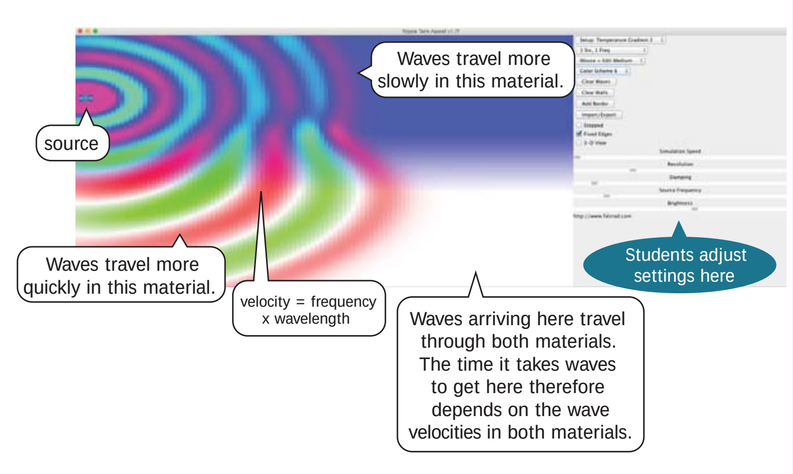

Diagram by M. d'Alessio

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Mr. J wanted students to use their **mathematical thinking [SEP-5]** to learn even more about rocks. Mr. J performed an example calculation of how long P-waves take to travel 10 km in solid rock (just 1.7 seconds at 6,000 m/s) versus dry sand (20 seconds at 500 m/s). These differences are amazing because they allow us to determine the type of rock beneath our feet without even lifting a shovel to dig. Mr. J then presented students with measurements from a few different earthquakes recorded at different locations. The data table showed the time it took waves to arrive at each location and the distance between that location and the earthquake source. He also provided students a table of typical wave speeds of common rock and soil materials. Mr. J asked students to **analyze and interpret [SEP-4]** these data by (1) calculating the average speed of the waves, and (2) identifying the dominant rock type around the earthquake source in each situation (supports HS-PS4-1). Scientists use this exact approach to determine the types of material present at different depths in the Earth in a way that is very similar to some medical imaging technology like X-rays and MRIs. For homework, Mr. J assigned students a video clip that showed how to use seismic waves to locate pockets of oil and gas, map out faults before earthquakes happen, and estimate the storage capacity of a natural groundwater aquifer. Students chose one of these earth science applications and created a one-page infographic **communicating [SEP-8]** the way that technology enables scientists to learn information about Earth materials through which waves travel (HS-PS4-5). They illustrated the path seismic waves would take through this system and the different wave speeds in the different materials.

Day 8: Probing Earth’s Interior II: Seismic Tomography

Investigative phenomenon: Waves from an earthquake on one side of the Earth travel all the way through the planet to the other side.

Mr. J told students that they were now ready to use seismic waves to probe deep inside the Earth to strengthen their **model [SEP-2]** of Earth’s interior from IS4 (HS-ESS2-1). One-half of the class played the role of theoretical seismologists and calculated the amount of time it would take waves to travel through the planet, assuming that the waves traveled at a constant speed (CA CCSSM N-Q.1, F-BF.1). The other half of the class acted as observational seismologists and analyzed data from actual earthquakes to determine the actual travel times of P-waves and S-waves. When the two groups compared their results, there was a point where the data and observations begin to be noticeably different, and students were able to determine the depth corresponding to this discontinuity using simple geometry (CA CCSSMG-CO.1, G-CO.12, G-C.5). They had now used seismic waves to discover the boundary between Earth’s mantle and its outer core. The different seismic wave speeds they observed reflect different densities that promote convection in Earth’s mantle (causing plate tectonics) and outer core (causing Earth’s magnetic field that protects the surface from damaging radiation in the solar wind ultimately allowing life to flourish) (HS-ESS2-1). (Adapted from DLESE Teaching Boxes n.d.)

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Vignette Debrief

Using earthquakes to motivate the study of waves allowed students to see how the abstract quantities of wave velocity, wavelength, and amplitude have real-world applications.

SEPs. The practice of **developing and using models [SEP-2]** was a key focus throughout the vignette. Some of the models were physical (the toy spring on days 2–3 and 6–8, and the two kinesthetic activities during days 2–3), some were mathematical (the movement of waves through materials at different speeds on days 6, 7, and 8 and the relationship between frequency, wavelength, and velocity on day 5), some were pictorial (like the model of Earth's interior developed on day 8), and some were mental models based on analogy (like the tortoise and hare fable from day 1 and the lightning and thunder analogy on days 2–3). Students also engaged in **mathematical thinking [SEP-5]** throughout the activity to answer fundamental questions such as which frequency seismic waves would damage buildings the most on day 5 and which earth materials had waves traveled through on days 6–7 and 8. Mr. J intentionally allowed the students unstructured exploration of the ripple tank simulator on days 6–7 to allow them to engage in **asking questions [SEP-1]**. It would have been quicker to direct students to a specific scenario within the simulator, but allowing them free reign to **investigate [SEP-3]** questions that interested them gave them a crucial baseline understanding of what the simulator actually represents. It could have also been the jumping off point for more detailed investigations into other aspects of wave behavior. The simulator allowed for qualitative investigations, but the students also did more detailed investigations into the velocity of waves on the spring using frame-by-frame video analysis during days 6–7. In several instances they briefly collected data from seismograms so that it could be **analyzed [SEP-4]**, usually using their smartphones or other technology to submit their data so that the whole class could see **patterns [CCC-1]** instantly. The performance expectations pertaining to waves do not emphasize scientific argument or explanation, but **communicating [SEP-8]** understanding is accomplished specifically using the concept of infographics on day 1 and again on days 6–7.

DCIs. The vignette used an Earth science phenomenon (earthquakes) to motivate detailed understanding of a physical science concept (waves). The relationship is not one way—the physical understanding enhances understanding of the Earth science phenomena, especially on days 2–3 when an understanding of the nature of longitudinal and shear waves allowed students to explain the strength and timing of the two pulses of shaking and on the last day when understanding wave velocities allowed students to probe the interior of the Earth (PS4.A). Seismic recording devices were a key technology discussed throughout the instructional segment, and there was explicit attention paid to how these systems were engineered during the discussion of new earthquake early-warning systems (mitigating natural hazards ESS3.B) on days 2–3 and the digital transmission of seismic data on day 4 (PS4.C). The concept of earthquake engineering was briefly introduced on day 5, but would ideally be extended to include a full engineering design activity involving a shake table that integrated concepts of forces and motion (PS2.A) with wave resonance. Both earthquake early warning

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and earthquake engineering are key concepts in which science and engineering can benefit society by saving lives (ETS2.B). Technology tools such as frame-by-frame video analysis and computer simulations allowed students to visualize the physical systems in ways that would not be possible without technology (ETS2.A).

CCCs. Waves themselves are examples of repeating **patterns [CCC-1]** of motion. At several times during the vignette, students made observations and were then asked to quantify them (the time between arrival of different pulses on day 1, the amplitude of those pulses on days 2–3, and the velocity of waves during days 6–8). Not only did this help establish the **quantity [CCC-3]**, but **patterns [CCC-1]** in these measurements revealed **proportional [CCC-3]** relationships in two cases: the time between earthquake waves was directly proportional to their distance from the earthquake source (day 1) and the speed of waves was directly proportional to the tension from stretching in the spring (days 6–8).

EP&Cs. This lesson did not explore environmental principles. Earthquakes and plate tectonics are part of a natural cycle that can impact ecosystems, but this lesson sequence focuses only on the impacts on humans.

CA CCSS Connections to English Language Arts and Mathematics. Throughout the vignette, students participated in small group and whole class discussions (SL.11–12.1a–d). The students also produced several types of writing including a short reflective essay as well as the creation of infographics (WHST.9–10.1a–e, 6, 7, 9). In the vignette, half of the class calculated the amount of time it would take waves to travel through the planet, assuming that the waves traveled at a constant speed (N-Q.1, F-BF.1). The other half of the class acted as observational seismologists and analyzed data from actual earthquakes to determine their actual travel time. When the two groups compared their results, there was a point where the data and observations began to be noticeably different, and students were able to determine the depth corresponding to this discontinuity using simple geometry (CA CCSSM G-CO.1, G-CO.12, G-C.5).

Resources

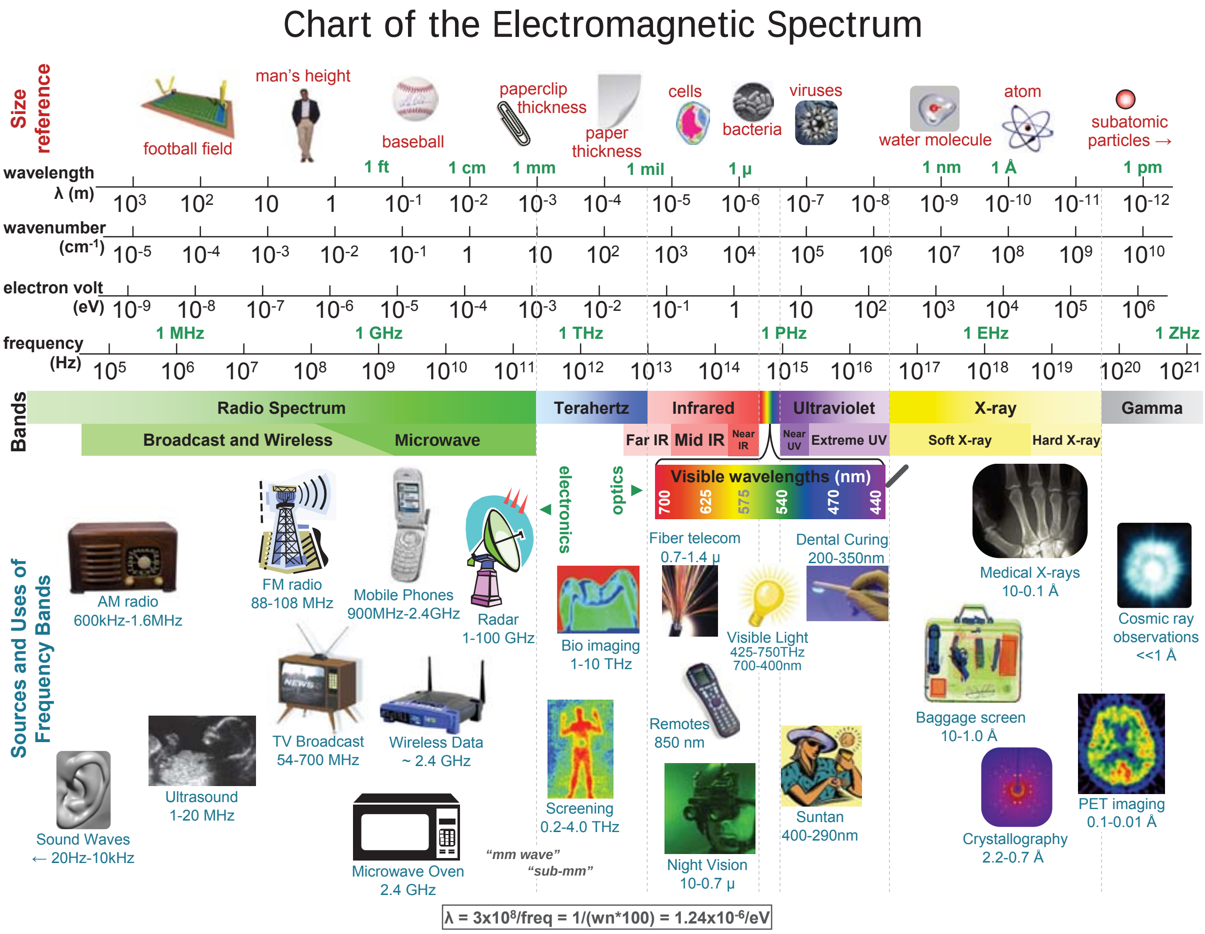
California State University Northridge. n.d. Earthquake Early Warning Simulator. http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link65.

Rapid Earthquake Viewer. n.d. http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link66.

The Nature of Light

Students can also relate the mathematical representations of amplitude and frequency to electromagnetic waves by comparing light bulbs with different wattage and color temperature (e.g., packages labeled soft white versus daylight). Knowing that the wavelength of light **changes [CCC-7]** its color, students are ready to learn more about the range of different frequencies of radiation in the electromagnetic spectrum. Electromagnetic radiation is an **energy [CCC-5]** form composed of oscillating electric and magnetic fields that propagates at the speed of light. There is a spectrum of electromagnetic radiation from the lowest frequency radio waves to microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays, and up to the highest frequency gamma rays (figure 7.61). Different frequency electromagnetic waves have different uses. Gamma rays are used to kill cancer cells in radiation therapy, X-rays are used to create noninvasive medical imagery, ultra-violet light is used to sterilize equipment, visible light is used for photography, infrared light is used for night vision, microwaves are used for cooking, and radio waves are used for communication. Plants capture visible electromagnetic radiation (sunlight) and use the energy to fix carbon into simple sugars during photosynthesis.

Figure 7.61. The Electromagnetic Spectrum



As students learn the physics of electromagnetic radiation, they also should learn the variety of applications that improve our quality of life. *Source*: Southwestern Universities Research Association 2006

Even though electromagnetic radiation can clearly be described using waves and its behavior in most situations can be predicted using this model, over the years scientists have discovered certain cases where light acts more like a collection of discrete particles than a wave. Students **obtain, evaluate, and communicate information [SEP-8]** pertaining to the wave/particle duality of electromagnetic radiation, which has been one of the great paradoxes in science (HS-PS4-3). As early as the seventeenth century, Christiaan Huygens proposed that light travels as a wave, while Isaac Newton proposed that it traveled as particles. This apparent paradox ultimately led to a complete rethinking of the nature of **matter and energy [CCC-5]**. Taken together, the work of Max Planck, Albert Einstein, Louis de Broglie, Arthur Compton, Niels Bohr, and many others suggests all particles also have a wave nature, and all waves have a particle nature. Students examine experimental **evidence that supports the claim [SEP-7]** that light is a wave phenomenon and **evidence that supports the claim [SEP-7]** that light is a particle phenomenon. After **analyzing and interpreting data [SEP-4]** from classic experiments on resonance, interference, diffraction and the photoelectric effect, students should be able to **construct an argument [SEP-7]** defending the wave/particle model of light.

One of the primary pieces of evidence for the particle nature of light is the photoelectric effect, the observation that many metals emit electrons when light shines on them. If light acts as a wave, electrons should be emitted for any frequency of light as long as the amplitude is high enough (i.e., if the wave carries enough energy). Data, however, show that electrons are only dislodged for light above a certain threshold frequency regardless of the intensity of the light. This result suggests that light is actually made of discrete particles (photons). The visual intensity of light depends on the number of particles arriving in a given time, but an electron only gets dislodged when an individual photon crashes into the metal with energy greater than the energy that binds the electron to the metal. Each photon has energy (E) proportional to its frequency (f). Expressed algebraically, we now accept that $E = hf$ where h is Planck's constant (a physical constant from quantum mechanics). Students can make a physical **model [SEP-2]** of the photoelectric effect with water representing continuous waves of light energy and different size marbles and ball bearings representing different frequencies of discrete photons of light energy. Additional marbles gently taped to a tabletop represent the electrons bound to the metal. Under the wave model of light, the electron marbles should stay still for a tiny stream of water (low-intensity light), but will roll away if the water gets poured fast enough (high-intensity light). In the particle model of light, intense light can be represented by lots of particles being dropped down at once. If those particles are small like ball bearings, no individual particle has enough energy to dislodge the electron marbles. However, a single large marble (a low-intensity light at a high frequency) can dislodge an electron.

In physics, radiation simply means the emission of energy. In IS3, students created models of radiation related to nuclear processes and asked questions about possible health impacts of that radiation. In IS4, they examined electromagnetic radiation. Does it have possible health impacts as well? Students know that they can get sunburned from ultraviolet (UV) radiation, so it is natural for them to be concerned about the effects of other types of radiation like radio waves from cell phones or wireless Internet. Performance expectation HS-PS4-4 requires students to evaluate the validity and reliability of claims in published materials of the effects that different frequencies of electromagnetic radiation have when absorbed by matter. To meet this performance expectation, students can **obtain and evaluate information [SEP-8]** and arguments put forth in books, magazines, Web sites, and videos. While the damaging effects of high-energy gamma rays, X-rays, and UV rays are well documented, the potentially damaging effects of microwave radiation (which includes the frequencies used by most mobile phones) are much more questionable. Students apply their model of the particle nature of light from the photoelectric effect to evaluate these claims. Microwave photons are lower frequency and therefore lower energy than damaging UV light, so they do not have enough energy to break chemical bonds. Students know that they can sit beneath regular lights all day long and do not get a sunburn. Analogous to the photoelectric effect, microwaves, with even lower energy photons, are still absorbed by the body causing it to heat up. Could this slight heating cause health impacts? Students can read an article (for example, the UC Museum of Paleontology 2016 article "A Scientific Approach to Life: A Science Toolkit" at http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link67) about how to identify credible sources of scientific information in the popular media. Then, each student can search and find one Internet resource about the topic. Students then conduct a virtual gallery walk during which they copy and paste the resource into a collaborative Web document, and other students make digital comments on the document, highlighting and identifying which aspects of the resource make it more or less credible and where the text refers to scientific concepts from the course. (Students could also print the resources and post them around the room so that peers can comment on them using sticky notes for a physical gallery walk).

Waves and Technology

Waves can encode information, and technology makes use of this fact in two general ways: (1) decoding wave interactions with media and (2) encoding our own signals using waves. Students must select one or more of these technologies and **communicate [SEP-8]** how wave properties enable the technology to function (HS-PS4-5). They could prepare a short fact sheet, a report, an interactive Web page, or other communication product that includes labeled diagrams (pictorial **models [SEP-2]**) illustrating key interactions between waves and matter. They can then orally present their communications product to the class.

In some technology, we simply record waves as they travel through a medium and use our understanding of how they travel to learn about the medium itself. Medical imaging (e.g., magnetic resonance imaging [MRIs] and X-rays) is one example, while seismic recording devices that detect seismic waves are another. Both of these tools have a long history. In 1895 the German physicist Wilhelm Röntgen discovered a high-**energy [CCC-5]**, invisible form of light known as X-rays. Röntgen noticed that a fluorescent screen in his laboratory began to glow when a high-voltage fluorescent light was turned on, even though the fluorescent screen was blocked from the light. Roentgen hypothesized that he was dealing with a new kind of ray that could pass through some solid objects such as the screen surrounding his light. Röntgen had an engineering mind, and realized that there could be practical applications of this newly discovered form of radiation, particularly when he made an X-ray image of his wife's hand, showing a silhouette of her bones. Röntgen immediately communicated his discovery through a paper and a presentation to the local medical society, and the field of medical imaging was born.

In other technology, engineers have learned how to add waves together to encode signals on them. Italian scientist Guglielmo Marconi learned how to harness electromagnetic waves to build the first commercially successful wireless telegraphy system in 1894, harnessing radio waves to transmit information. Information can be encoded on radio waves in a variety of manners, including pulsating transmissions to send Morse code, modulating frequency in FM radio transmission, modulating amplitude in AM radio transmission, and propagating discrete pulses of voltage in digital data transmission. Students can use computer simulations or even oscilloscope apps on computers and smartphones to visualize how each of these techniques affects the shape of waveforms. Wireless transmission has revolutionized human communication and is at the heart of the Information Revolution, which is arguably one of the biggest shifts in human civilization on par with the agricultural and industrial revolutions.

Performance expectation HS-PS4-2 requires students to "evaluate questions about the advantages of using digital transmission and storage of information." By **analyzing and interpreting data [SEP-4]** about digital information technologies and similarly purposed analog technologies, students can meet this performance expectation. By comparing and contrasting such features as data transmission, response to noise, flexibility, bandwidth use, power usage, error potential, and applicability, students can assess the relative merits of digital and analog technologies. This performance expectation requires students to ponder the influence of those technologies that have shaped our modern world. As students evaluate digital transmission and storage of information, they begin to understand the **influence of science, engineering, and technology on society and the natural world [CCC about the nature of science]**, learning how scientists and engineers have applied physical principles to achieve technological goals and how the resulting technologies have gained prominence in the marketplace and have influenced society and culture.