Physics in the Universe: Unit 5

Electromagnetic Radiation

Background for Teachers and Instructional Suggestions

In the previous instructional segment, students found **evidence** 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. 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 learn to **explain** the differences between the way these ***energy*** sources travel and how fast they travel.

In many physics books, light, sound and other wave phenomena are described as "ways ***energy*** is transmitted without an overall ***flow of matter***". Such descriptions are important for understanding such things as the transmission of energy from nuclear reactions in the Sun across space to a solar panel that generates electricity, the transmission of sound energy from a performer on stage through the air to listeners throughout an auditorium, or the violent shaking in an earthquake traveling through solid rock from its source to a nearby city. However, a second aspect of light, sound, and other wave phenomena is also important, namely that they encode information, and hence are a critical tool for how we learn about and interact with the world around us. This is true not only for our natural senses, as stressed in earlier grades, but for the tools and technologies that we build and use, both for science and for everyday communication and information storage.

While students are most familiar with light and sound, each of these is representative of the two broader classes of waves: mechanical and electromagnetic. Mechanical waves propagate through a medium, deforming the substance of this medium. The deformation is reversed due to restoring forces that act within the medium.

For example, sound waves in the atmosphere propagate as 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 over long distances. Light is an example of the second type of waves, electromagnetic. These do not require a medium for transmission, so they can travel through empty space. Electromagnetic waves consist of periodic oscillations of electrical and magnetic fields generated by charged particles. The frequency (or conversely the wavelength) of electromagnetic waves determine the properties of the waves. There is a spectrum of electromagnetic radiation including radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays. Radio waves exhibit the lowest frequency (longest wavelength) and energy, while gamma rays exhibit the highest frequency (shortest wavelength) and energy.

The medium that waves travel through has a huge impact on the speed at which the ***energy*** 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 which 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 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. 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 the snapshot on geometric spreading in instructional segment 2) 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 the previous instructional segment, students **interpreted data** from radiometric dating to discover that there is no seafloor older than 280 million years and then **asked questions** about where it could have gone. With seismic tomography, they can gather **evidence** that answers this question – it is sinking into Earth's interior.

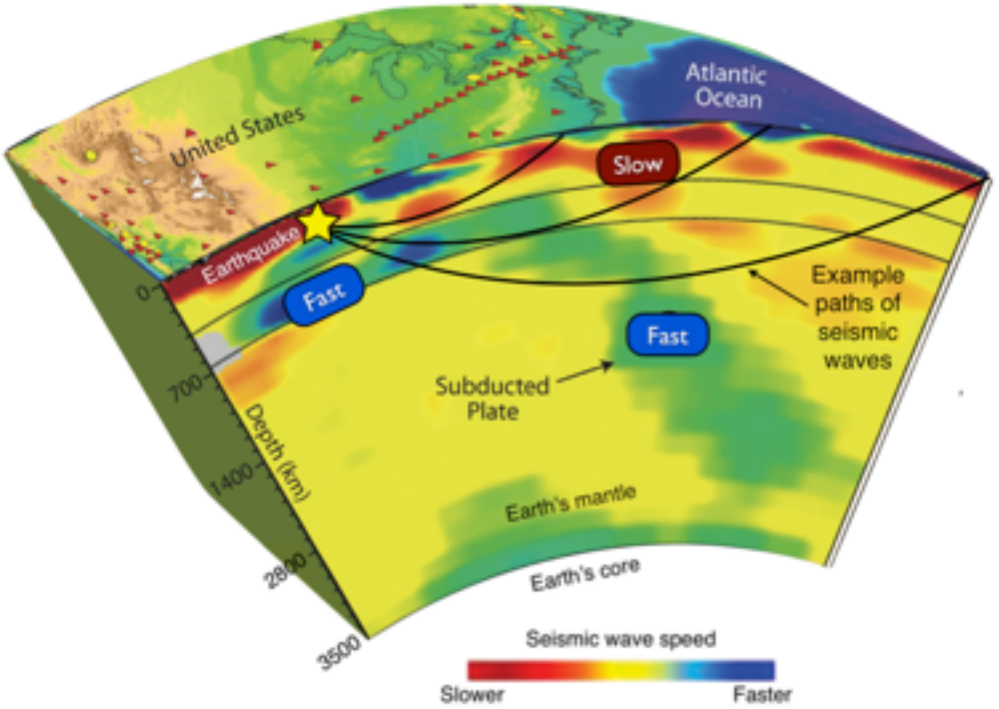


Figure 9. Seismic waves move faster or slower as they move through different materials. Seismologists use this fact to map out the structure of Earth's interior. This image reveals evidence of plate tectonics and California's geologic history. The remnants of a large plate sinking beneath North America 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 mountains).

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 propagate. Liquids do have strong resistance to compression, so 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 instructional segment 3). 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.

High School Vignette

Seismic waves

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 could be used to begin an instructional segment on waves in the Physical Universe course. Students learn ESS 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 slinky 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.

Day 1 – Observing earthquakes

The first day of the lesson, Mr. J wants 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 wants students to discover these ideas for themselves and has designed a data-rich inquiry-based lesson. He recognizes this lesson takes a lot more time than just providing them the answer, but he knows they will have more 'aha moments' if they figure it out themselves. Mr. J asks students if anyone has ever felt an earthquake. A few students raise their hands and he asks them to describe what they felt, and to specifically show him with their hands the direction that their body moved during the earthquake. Some students move their hands side to side or shake them up and down. Mr. J emphasizes the differences, but highlights that one thing everyone shares in common is that the motion repeated back and forth many times, which means that they can describe the motion with waves. He begins to build a definition of waves that they will add to throughout the next few days as they lean new things.

Man eating lunch feels mild shaking; He looks up.

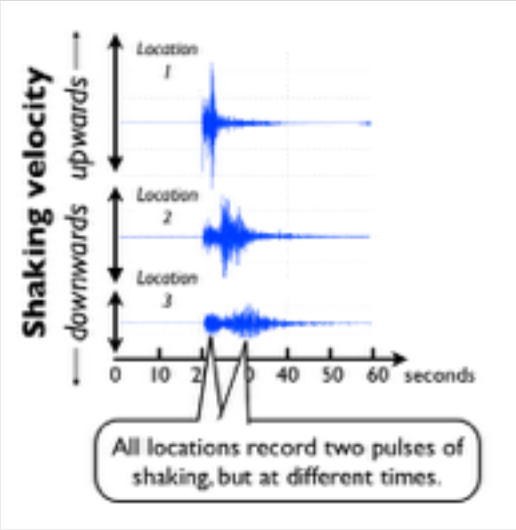
People in office recognize shaking as an earthquake. Race to leave room.

Strong shaking begins.

Peak shaking occurs.

Earthquake is over.

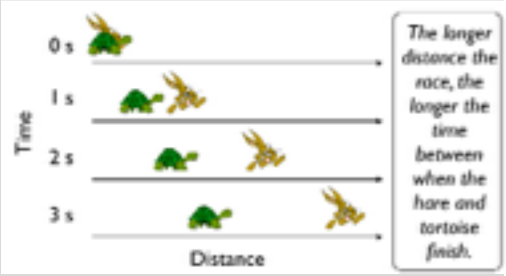
Mr. J shows a short video clip of a web camera that happened to be recording during an earthquake while a man was sitting and eating his lunch. He reacts to gentle shaking at the beginning of the earthquake several seconds before strong shaking begins. Mr. J wonders if this is always true, and tells students that sensitive seismic recording devices measure shaking at different locations all around their city. He passes out papers with measurements of a single earthquake from different locations. Mr. J makes sure that students understand the axes and what the graph represents (how fast the earth was moving and in which direction over the course of an entire minute). Each student receives the recording from a different location, but all students recognize that their location felt two pulses of shaking. Sally **asks** if maybe there were two earthquakes, one big and one small but just a few seconds apart. Mr. J agrees that this is a good idea and asks her to how many seconds apart the two pulses were on her recording (***scale, proportion, and quantity***). “The second one happened about 10 seconds after the first,” she says. Mr. J asks if other students also have the second pulse 10 seconds after the first and they find that every student seems to have a different time between pulses even though they are all recording the same earthquake on the same day. Why? Students compare



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

seismograms and notice that the amplitude of the shaking is different. Evan **asks** Mr. J if stations with stronger amplitude shaking are closer to the earthquake source, and Mr. J confirms that this is, in general, true. He asks the students to see if there is any systematic relationship between the time difference between the pulses and how far the sensor was away from the earthquake source. Students use their phones to enter the amplitude and arrival time of the two pulses from their assigned location into a collaborative spreadsheet that Mr. J has already set up. It instantly graphs the relationship and students can see that the farther away a station is from the earthquake source, the further apart the two pulses are.

Mr. J then has two student volunteers act out the famous fable of a race between the tortoise and the hare as he narrates. Seismic waves, however, never take a nap like the hare in that story. For homework, Mr. J assigns students to create a visual infographic **communicating** an **explanation** about why the two pulses of energy arrive at different times at different locations. Their examples show that the two waves travel at different speeds.



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

In an earthquake, people can certainly feel waves moving back and forth and at the ocean they can see them moving towards the beach. Do these two observations relate to the same type of phenomenon? Mr. J gives a short interactive lecture about mechanical waves, adding to the definition of waves the class 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’s hard to make waves in clay because it doesn’t 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 really well across a swimming pool 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 foreshadows that they will discuss the topic a lot more in a few days.

Mr. J demonstrates waves using a physical **model**, a toy spring stretched out across the room. He asks students why he has chosen a spring for the demo instead of a piece of rope and students quickly identify that the spring will easily want to pop back into position. He shows 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[1]. The waves go by very quickly on the spring, so Mr. J has students stand up and use their bodies as a physical **model** that represent the links of a slinky to act out the particle motion of the different types of waves[2].

Mr. J wants to relate these two types of waves to the seismic recordings from Day 1. He passes them out again and asks students to look more carefully at the two pulses. How are they similar and how are they different? Students offer observations from their own seismograms, including Jorge's comment that the second pulse is stronger than the first. Like yesterday, Mr. J wants to see if there are consistent ***patterns*** across all the seismograms. He has them measure the amplitude of the two pulses and submit their results to an online form using their smartphones. The class instantly **analyzes** the results from a graph projected on the screen and determines that almost all the locations experienced stronger shaking during the second pulse. Why would that be?

Now that Mr. J has students curious, he shows a mini-lecture: Much like a storm cloud simultaneously produces lightning and thunder, earthquake waves release energy as both of these types of waves. As the blocks of crust slide past one another, the Earth is disturbed in several 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

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[1] IRIS, Seismic Slinky, http://www.iris.edu/hq/inclass/video/seismic_slinky_modeling_p_and_s_waves_in_the_classroom

[2] IRIS, Human Wave Demonstration, http://www.iris.edu/hq/inclass/demo/human_wave

pulling of one section of rock against another. Because rocks are very strong when you push on them, this energy moves easily through rock and P-waves travel fast and arrive first. While they arrive quickly, relatively little energy is released as pushing/pulling, so P-waves don't 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. Rock is weaker in shear than it is for pushing/pulling, so S-waves move more slowly through it. S-waves arrive second, but carry the powerful punch that causes great earthquake damage. The analogy with lightning and thunder holds, you quickly see lightning several seconds before booming thunder reaches you to rattle your windows.

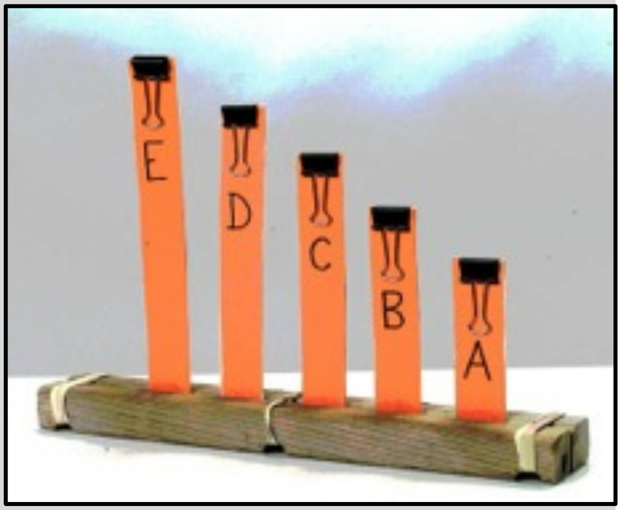
Students will explore wave speed more in a few days, but right now Mr. J tells them that they need to remember that P-waves travel faster than S-waves, but S-waves carry more energy when they finally do arrive. The fact that every earthquake comes with its own 'gentle' warning (a P-wave) has allowed scientists and engineers to develop systems to provide cities with advance warning of strong shaking. Mr. J shows students a short video clip about earthquake early warning systems. The video describes 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 takes the class outside to the sports field and has them use their bodies as a physical **model** of slow P-waves and fast S-waves in a kinesthetic activity that illustrates 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 even developing its own early warning. For homework, Mr. J assigns students to watch a few short YouTube videos of early warning in action during earthquakes in Japan and Mexico and assigns 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

Earthquake early warning works because information from seismic recording stations in many different locations can send their measurements to a central processing center instantly. In order to avoid costly false alarms or failing to issue a warning about a damaging earthquake, the information must be transmitted reliably. Mr. J tells students that they will develop a technique for transmitting the shaking history shown by their seismogram to the students other side of the room using a small desk lamp with a dimmer attached to it. In middle school, students obtained information about the difference between analog and digital information transmission (*MS-PS4-3*), and today students will compare the two (*HS-PS4-2*). Half of the teams will transmit 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 will come 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 a individual blinks to be counted). Teams can summarize their encoding protocol before beginning transmission so that everyone knows how to interpret the signals from the light. Without seeing the original seismogram, the team on the other side of the room must draw what they think the seismogram looks like based upon the signal transmitted to them and the agreed upon protocol. Students receiving the analog signal have trouble representing the shape of the signal as the solutions drawn by different students vary dramatically. Mr. J then asks what would happen if he gave students a seismogram with an amplitude just one tenth as strong as the one that they had. With the analog signal, the light gets very dim and it would be 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 reports 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 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

Mr. J starts the class off by showing a video of a life size apartment building being tested on a gigantic shake table[3]. Is a seven story apartment building safer or less safe than a one story house? How about a 100 story skyscraper? Mr J. tells students that they are going to simulate buildings using a much simpler physical **model**. They will model a city using different length rectangles of heavy paper to represent different height buildings[4]. They attach the rectangles to a ruler that represents the ground and attach a paperclip to the top of each building to represent air conditioners and other heavy objects on the buildings' roofs.



Mr. J then asks students which building they would rather live in during an earthquake. Different students have different ideas, so he invites everyone to shake their city. Sammy is very aggressive and shakes her city back and forth very quickly and is amazed to see that the shortest building starts moving more than the others. Roland shakes more slowly and sees the opposite effect with the tallest building moving more than the others. This allows Mr. J to add to the class definition of waves, adding that they can be described by the frequency at which they move back and forth. Mr. J asks the students to describe their shaking using the words frequency and amplitude instead of just saying 'quickly' or 'slowly.' He asks students to do a more controlled experiment where they shake with a constant amplitude (distance their hand moves back and forth), but change the frequency of shaking (how quickly their hands

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[3] World's largest earthquake test, https://youtu.be/9X-js9gXSME

[4] IRIS, Demonstrating building resonance using the simplified BOSS model, http://www.iris.edu/hq/inclass/demo/demonstrating_building_resonance_using_the_simplified_boss_model

moves from one extreme to the other) from a low frequency to a high frequency and watch what happens to the buildings. He then asks 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*** in the shaking of the buildings?	Yes, first the tallest progressing to the smallest.
What controlled which buildings shook?	Students resort back to using terms like how "fast", "quickly", or "much" they moved their hand during the demo. Mr. J guides 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.
Lets 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 returns 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** shook the most when their height matched the wavelength of the waves, a phenomenon called resonance. Mr. J provides a short lecture with demos using a string to visualize resonance in standing waves. He then presents a **mathematical** model, the equation *speed = frequency x wavelength*. The students perform some simple calculations to ensure that they can plug numbers in and handle the units of this equation (*HS-PS4-1*).

Mr. J heard stories of people looking out over a valley during a large earthquake and literally seeing the earth ripple as waves passed through. He wants to know if this is reasonable. What would seismic waves look like? At the beach, ocean waves might have crests that are 30 feet apart (wavelength = 30 ft). What about seismic waves? Students return to their adopted seismic recording and look more carefully at the shaking. Mr. J asks students to calculate the frequency of the seismic waves during the earliest shaking. They might find 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 calculate the wavelength. Looking across a valley a bit more than a mile across, you might be able to see 2 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.

Mr. J next shows video clips with the results of computer simulations of famous California earthquakes[5]. Making detailed measurements from the computer screen, students calculate 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 verify that they get the same result from each equation. They then compare these computer models to a video that visualizes ripples as they were recorded by a very sophisticated network of seismic sensors during a much smaller earthquake[6]. Students discover that the velocity is quite similar in the two cases, but that the frequency and wavelength differ for different size earthquakes. This motivates the next activity relating seismic wave velocities to the properties of the materials.

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[5] USGS, Computer Simulations of Earthquakes for Teachers: http://earthquake.usgs.gov/regional/nca/simulations/classroom.php

[6] AGI, Watch the ground ripple in Long Beach, http://blogs.agu.org/tremblingearth/2012/12/17/watch-the-ground-ripple-in-long-beach/

http://blogs.agu.org/tremblingearth/2012/12/17/watch-the-ground-ripple-in-long-beach/

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

Mr. J starts class with a rock and a bucket of sand on the table and asks students whether they think seismic waves could travel through either of them. Most students answer no because they don't think that either one would pop back into place like a spring. He asks them if the two different materials respond to force differently, or "Would it hurt the same amount if you fell on the solid rock versus the soft sand?" Mr. J tells them that by the end of the day, they will hopefully understand some of the differences between the materials.

Mr. J returns to the physical **model** of the toy spring and illustrates a few more 'example earthquakes.' He shows gentle disturbances and big disturbances (changing 'amplitude') and changes the amount of stretch in the spring by pulling it longer or shorter before he causes the next earthquake. Students can't visually see any consistent ***patterns*** because the spring moves so quickly, but a student records a video of the demonstration. Groups download the video and open it in a free video analysis software[7] so that they can watch it in slow motion and measure and compare the speed of the waves in several sample earthquakes. When students **analyze the data**, they find that the speed the waves traveled was ***proportional*** to the length of the spring as it was stretched out longer or shorter. Students are surprised to see that the amplitude of the disturbance doesn't make much of a difference to the wave speed. Mr. J ends class by having students write an **explanation** describing the factors affecting wave speeds, giving them a sentence starter to "The speed waves travel along a spring depends on ______."

Mr. J returns to class the next day to the bucket of sand and the rock on the table. He asks students to work in pairs to draw a diagram that shows how the investigation of the loose versus stretched spring might be a good **model** for the way seismic waves might travel differently through the two materials. Olivia and Martin make 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 validates

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[7] Brown, D. 2015. Tracker video analysis and modeling tool, http://physlets.org/tracker/. Accessed October 16, 2015.

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***, and their sudden movements are strong enough to bend the rock like fingers temporarily bent the spring. In his honors class, Mr. J has students calculate wave speeds using equations that include the density and elastic modulus of the materials.

Mr. J has students open up a free computer simulation to **investigate** waves moving through a medium[8]. The simulator **models** the behaviors of all types of waves. While the class is thinking of them as seismic waves, they could be water, sound, or light waves. Working in groups, students have a full 10 minutes to explore the program selecting some of the preset scenarios in the program and adjusting settings. Each team will present the 'coolest' picture they made and have to **communicate** their understanding of what it shows about wave behavior. Mr. J walks around interacting with each group, encouraging them to **ask questions** about what will happen and then try things out. After each group shares, Mr. J draws attention to Esmerelda and Dima's scenario which shows what happens when waves travel through materials with different velocities. "This picture could be a slice through the Earth with different earth materials like sand on top of rock," says Mr. J. The waves leaving the source near the top left must travel through both materials to reach the bottom right. He points out how the wavelength of the source is different as the waves travel through the two materials, and

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[8] Ripple Tank, http://www.falstad.com/ripple/ (available as a JAVA app, Mac, Windows, and iOS)

asks students to estimate which material has a faster wave velocity (*HS-PS4-1*).

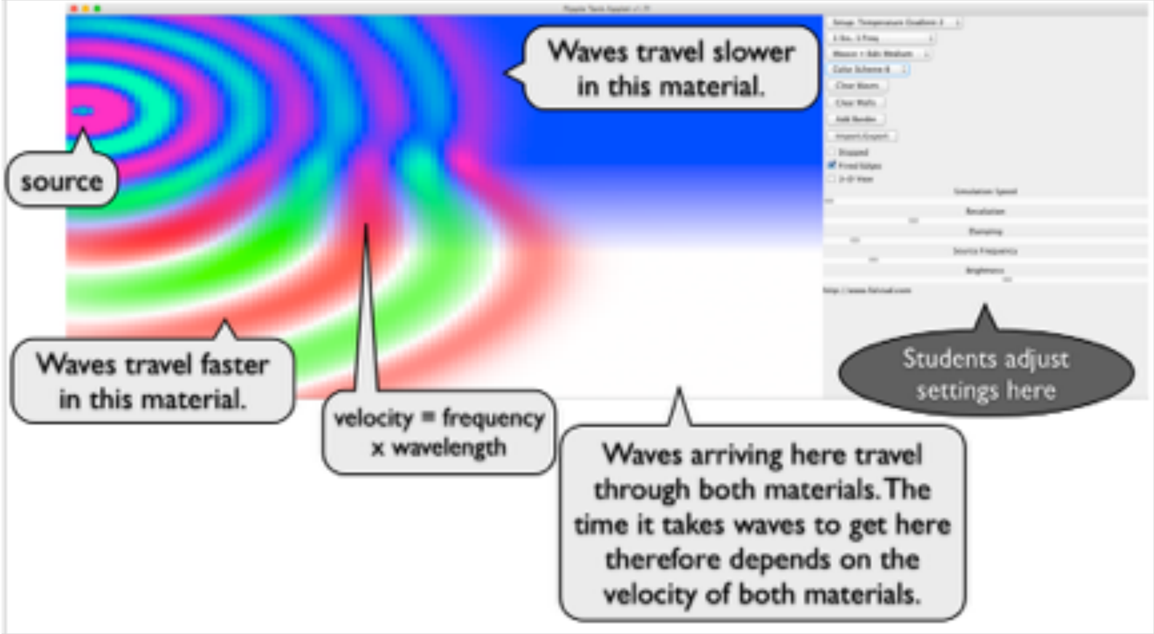

Image credit: M. d’Alessio

Mr. J wants students to use their **mathematical thinking** to learn even more about rocks. Mr. J performs an example calculation of how long P-waves will 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 presents students with measurements from a few different earthquakes recorded at different locations. The data table shows the time it takes waves to arrive at each location and the distance between that location and the earthquake source. He also provides students a table of typical wave speeds of common rock and soil materials. Mr. J asks students to **analyze and interpret** 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 MRI’s. For homework, Mr. J assigns students a video clip that shows examples of using 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 must choose one of these earth science applications and create a one page infographic **communicating** the way that technology enables scientists to learn information about the earth materials through which the waves travel (*HS-PS4-5*). They must illustrate the path seismic waves take through this system and the different wave speeds in the different materials.

Day 8 – Probing Earth's Interior II: Seismic Tomography

The next day, Mr. J tells students that they are now ready to use seismic waves to probe deep inside the Earth to strengthen their **model** of Earth's interior from instructional segment 4 (*HS-ESS2-1*). One-half of the class plays the role of theoretical seismologists and calculates the amount of time it will take waves to travel through the planet, assuming that the waves travel at a constant speed (*MATH.N-Q.1, F-BF.1*). The other half of the class acts as observational seismologists and analyzes data from actual earthquakes to determine their actual travel time. When the two groups compare their results, there is a point where the data and observations begin to be noticeably different, and students are able to determine the depth corresponding to this discontinuity using simple geometry (*MATH.G-CO.1, G-CO.12, G-C.5*). They have now used seismic waves to discover the boundary between Earth's mantle and outer core. The different seismic wave speeds they observe 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 2015)

Performance Expectations

HS-PS4-1 Waves and Their Applications in Technologies for Information Transfer

Use mathematical representations to support a claim regarding relationships among the frequency, wavelength, and speed of waves traveling in various media.

HS-PS4-5 Waves and Their Applications in Technologies for Information Transfer

*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.**

HS-PS4-2 Waves and Their Applications in Technologies for Information Transfer

Evaluate questions about the advantages of using a digital transmission and storage of information.

HS-ESS2-1 Earth's Systems

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.

Science and engineering practices	Disciplinary core ideas	Crosscutting concepts
Developing and Using Models **Planning and Carrying Out Investigations** **Analyzing and Interpreting Data** **Obtaining, Evaluating, and Communicating Information**	**PS4.A Wave Properties** **PS4.C Information Technologies and Instrumentation** **ESS2.B: Plate Tectonics and Large-Scale System Interactions** **ESS3.A Natural Resources** **ESS3.B Natural Hazards**	**Scale, Proportion, and Quantity** **Patterns** **Influence of Science, Engineering, and Technology on Society and the Natural World** **Science Addresses Questions About the Natural and Material World**

Connections to the CA CCSSM: *MATH.N-Q.1, F-BF.1, MATH.G-CO.1, G-CO.12, G-C.5*

Connections to CA CCSS for ELA/Literacy:

Connection to CA ELD Standards:

Connections to the CA EP & Cs: none

Vignette Debrief

Science and engineering practices. The practice of **developing and using models** is a key focus throughout the vignette. Some of the models are physical (the toy spring on Days 2-3 & 6-8, and the two kinesthetic activities during Days 2-3), some are 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 are pictorial (like the model of Earth's interior developed on Day 8), and some are 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 engage in **mathematical thinking** throughout the activity to answer fundamental questions such as which frequency seismic waves will damage buildings the most on Day 5 and which earth materials did waves travel through 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**. It would have been quicker to direct students to a specific scenario within the simulator, but allowing them free reign to **investigate** questions that interest them gives them a crucial baseline understanding of what the simulator actually represents. It could also be the jumping off point for more detailed investigations into other aspects of wave behavior. The simulator allows for qualitative investigations, but the students also do more detailed investigations into the velocity of waves on the spring using frame-by-frame video analysis during Days 6-7. They have several instances where they briefly collect data from seismograms so that it can be **analyzed**, usually using their smartphones or other technology to submit their data so that the whole class can see ***patterns*** instantly. The PE's pertaining to waves do not emphasize scientific argument or explanation, but **communicating** understanding is accomplished specifically using the concept of infographics on Day 1 and again on Days 6-7.

Disciplinary core ideas. The vignette uses 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 where an understanding of the nature of longitudinal and shear waves allows students to explain the strength and timing of the two pulses of shaking and on the last day where understanding wave velocities allow students to probe the interior of the Earth. Seismic recording devices are a key technology discussed throughout the instructional segment, and there is explicit attention to how these systems are engineered during the discussion of new earthquake early warning systems on Days 2-3 and the digital transmission of seismic data on Day 4. The concept of earthquake engineering is briefly introduced on Day 5, but would ideally be extended to include a full engineering design activity involving a shake table that integrate concepts of forces and motion with wave resonance. Both earthquake early warning and earthquake engineering are key concepts where science and engineering can benefit society by saving lives. Technology tools such as frame-by-frame video analysis and computer simulations allow students to visualize the physical systems in ways that would not be possible without technology.

Crosscutting concepts. Waves themselves are examples of repeating ***patterns*** 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***, but ***patterns*** in these measurements revealed ***proportional*** 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).

Resources for the Vignette

- California State University Northridge. 2015. Earthquake Early Warning Simulator. http://www.csun.edu/quake (accessed November 3, 2015).
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- Rapid Earthquake Viewer. 2015. http://rev.seis.sc.edu/ (accessed November 3, 2015).

Students extend the mathematical representation of waves they made at the middle grade level (*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 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.

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*** 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*** form composed of oscillating electric and magnetic fields that propagates at the speed of light. Electromagnetic radiation has a myriad of uses that are determined by its specific frequency and energy (Figure 10), with different ranges of frequencies given different names. Some examples of the many uses include: gamma radiation is 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 that subsequently provides food for all heterotrophic organisms.

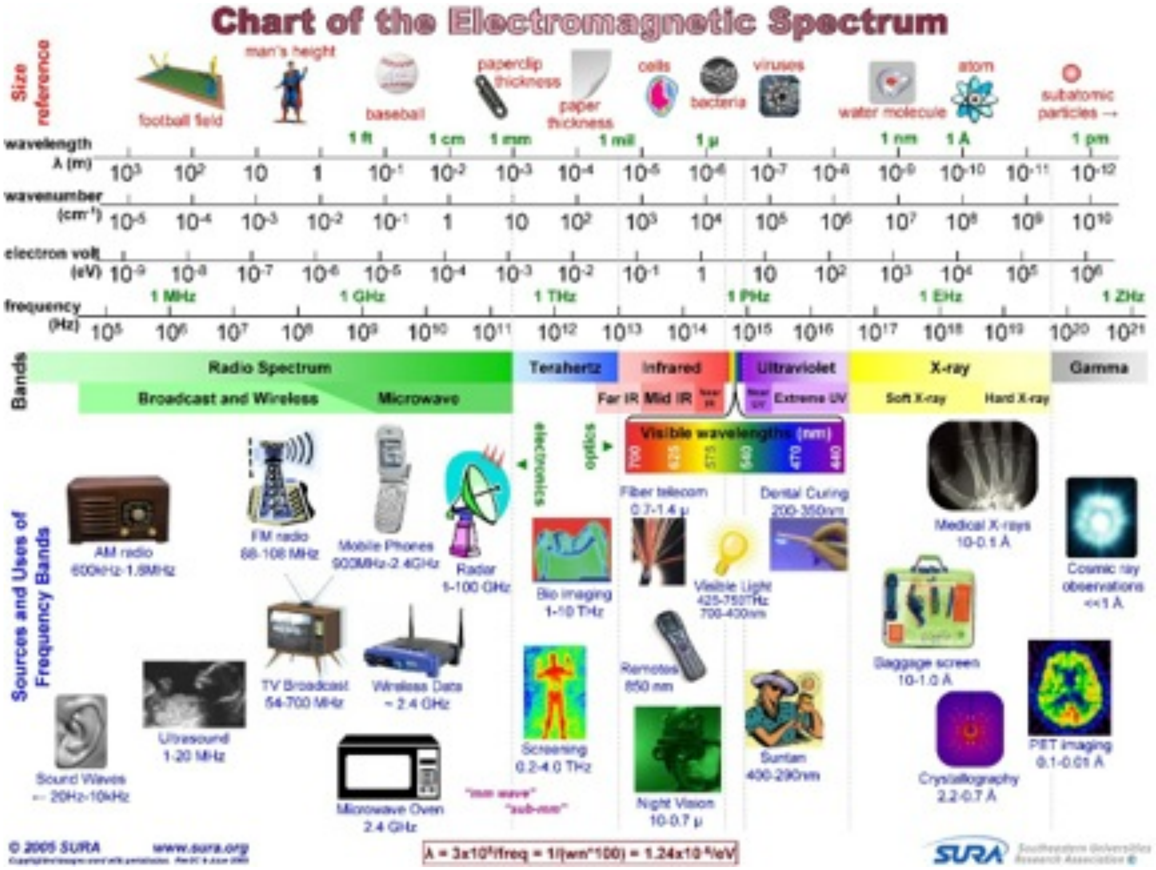

Figure 10. As students learn the physics of electromagnetic radiation, they also should learn the variety of applications that improve our quality of life. (Lightsources 2015)

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 collection of discrete particles than a wave. Students **obtain, evaluate, and communicate information** 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 17th 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***. Taken together, the work of Max Planck, Albert Einstein, Louis de Broglie, Arthur Compton and 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 that light is a wave phenomenon, and **evidence** that supports the claim that light is a particle phenomenon. After **analyzing and interpreting_data** from classic experiments on resonance, interference, diffraction and the photoelectric effect, students should be able to construct an **argument** defending the wave/particle model of light.

One of the primary lines of evidences for the particle nature of light is the photoelectric effect, the observation that many metals emit electrons when light shines upon them. Students saw evidence of this effect in instructional segment 3 when they studied the basic principles of photovoltaic solar panels. Now, they revisit the same challenge with a new understanding of the nature of light. Thinking of light as pure waves would suggest that photoelectrons could be emitted if the amplitude of any form of electromagnetic radiation is increased sufficiently, but data shows that electrons are only dislodged if light reaches or exceeds a threshold frequency, regardless of the intensity (amplitude) of the light. This suggests that light is a collection of discrete wave packets (photons), each with ***energy*** (E) proportional to its frequency (f). Expressed algebraically, we now accept that $E = hf$ where h is Planck's constant (the physical constant that is the quantum of action in quantum mechanics, the discipline that deals with the mathematical description of the motion and interaction of subatomic particles.). If the energy of a photon exceeds the electron binding energy in the metal, a photoelectron will be ejected. If, however, the photon energy is insufficient, no electrons will escape, regardless of the intensity of the radiation. Thus, the energy of the emitted electrons does not depend on the intensity (amplitude) of the incident light, but only on the energy of individual photons. Electrons in the metal can absorb energy from photons when irradiated, but they follow an "all or nothing" principle in that all of the energy from the photon must be absorbed to free an electron from atomic binding. If the photon energy is absorbed, some of the energy liberates the electron from the metal atom while the remainder contributes to its kinetic energy.

The photoelectric effect is one example of the way that matter and electromagnetic radiation interact. As humans have become increasingly dependent on electromagnetic radiation in their everyday lives through the use of technology, their exposure to certain types of electromagnetic radiation is increasing. Many in society have asked the question about what sort of interactions there may between living tissue and radiation. Students examine claims in published materials such as websites or books and use their understanding of the nature of electromagnetic energy to evaluate the validity of those claims (*HS-PS4-4*). The clarification statement for this PE specifically states that the materials should be ones that are likely to contain biases, so the emphasis is on ***evaluating information***. Teachers can build lessons that draw on existing educational resources describing how to interpret media messages and identify bias[9]. The key piece of scientific understanding is the model that photons of different frequency radiation have different amounts of ***energy*** (*$E = hf$, where E is energy, h is Planck's constant, and f is the frequency*). Higher frequency radiation such as gamma rays, X-rays, and ultraviolet correspond to higher energy levels and the damaging effects of exposure to these frequencies of radiation is well documented. Students probably have even experienced it for themselves as sunburn from ultraviolet light. One way this radiation can cause damage is by breaking chemical bonds in DNA that cause mutations that lead to cancer. On the other hand, people have no concerns about being exposed to visible light from light bulbs because these photons are substantially lower energy and cause no damage. It is the intermediate energy levels of the electromagnetic spectrum where many people are asking questions about potential health-related effects, such as the microwaves used in mobile phone transmission. Microwaves photons are lower energy than x-rays or other high frequency radiation, so they do not have enough energy to break chemical bonds (and therefore should not cause biological damage). Students have everyday experience with this fact in that their microwave oven will heat water and even boil it away into steam, but even microwaving the water for a very long time never breaks the molecules apart into their constituent hydrogen and oxygen atoms (Do not try this at home because the steam expansion could conceivably build up enough pressure within the microwave to explode). Indeed, there are peer-reviewed studies documenting no effect of mobile phone use on cancer rates, but there are also others that show a small statistical effect. Approximately one in four Californians dies from a wide range of cancers that have a wide range of environmental causes (American Cancer Society, California Department of Public

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[9] University of California Museum of Paleontology, A scientific approach to life: A science toolkit: http://undsci.berkeley.edu/article/sciencetoolkit_01

Health, California Cancer Registry 2014). Each of these people lives a different life in a different local environment, so it is extremely difficult (if not impossible) to isolate the effects of electromagnetic radiation on that cancer rate. This inability makes it difficult to make strong conclusions either way, but students should know that eventually any claim that these types of lower energy radiation cause health damage must include reasoning that **explains** the ***cause and effect*** mechanism (what does the radiation do to the tissue). That mechanism is well understood for high energy radiation like X-rays and has not been established for other types of radiation.

Waves and Technology

Waves can encode information, and technology makes use of this fact in two general ways: decoding wave interactions with mediums, and encoding our own signals on them.

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 like magnetic resonance imaging (MRIs) and X-rays and are 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***, 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 transmission 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.

HS-PS4-2 requires students to “evaluate questions about the advantages of using digital transmission and storage of information.” This performance objective can be met by **analyzing and interpreting data** regarding digital information technologies and similarly purposed analog technologies. 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 PE requires students to ponder the influence of those technologies on our modern world. As students evaluate digital transmission and storage of information, they learn 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**.**