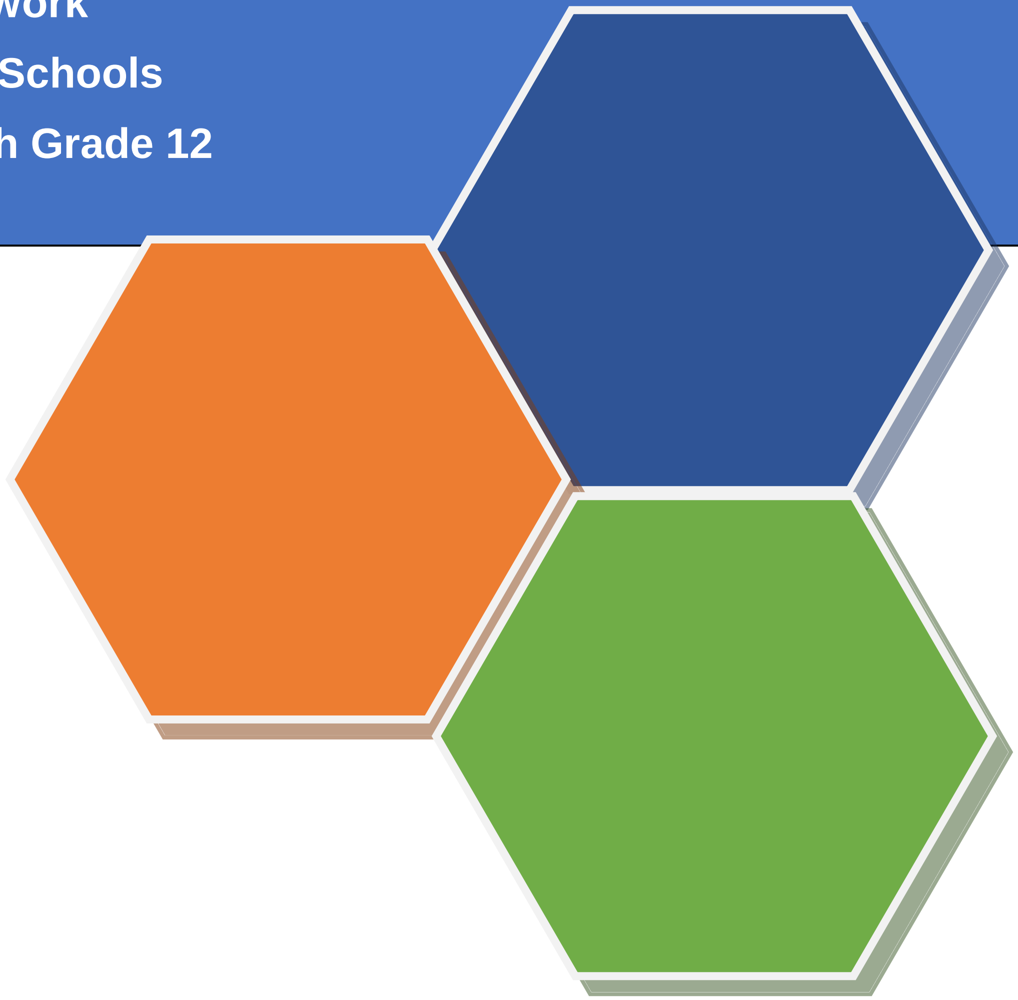
Chapter 7

High School Three Course Model

2016 Science Framework
for California Public Schools
Kindergarten through Grade 12



The *CA Science Framework* was adopted by the California State Board of Education on November 3, 2016.

Chapter 7

High School Three-Course Model

Introduction to Grades Nine Through Twelve

High School Three-Course Model Introduction

High School Three-Course Model

The Living Earth

Chemistry in the Earth System

For an additional high school course model see appendix 4 – High School Three-Year Model: Every Science, Every Year

Introduction to Grades Nine Through Twelve

The *National Research Council's A Framework for K–12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (NRC Framework)* outlined a significant new vision for science education. The Next Generation Science Standards for California Public Schools, Kindergarten Through Grade Twelve (CA NGSS), aided by the *Science Framework for California Public Schools: Kindergarten Through Grade Twelve* (*CA Science Framework*), are the first step toward translating that vision into practice.

Before schools and districts can fully implement the CA NGSS, they must organize the high school grade-banded performance expectations (PEs) into courses. This chapter describes ways in which the PEs for high school could be bundled together into units to form an appropriate sequence of courses. This chapter describes one of two high school course sequences: the High School Three-Course Model. The High School Four-Course Model is described in chapter 8. Additionally, appendix 4 in this *CA Science Framework* outlines an integrated three year high school model called "Every Science, Every Year."

Overall High School Three-course Model Introduction

The three-course model combines all high school performance expectations (PEs) into three courses. To highlight the nature of Earth and space science (ESS) as an interdisciplinary pursuit with crucial importance in California, each of the three courses present an integration of ESS and one of the other high school disciplines. In each course, the integration adds value to both disciplines in the pair, with each providing an engaging motivation for and a deeper insight into the other. ESS phenomena can serve as an engaging motivation for studying the other disciplines while understanding of each discipline provides deeper insight into processes in ESS. The three courses have been explicitly titled to emphasize this synergy:

- Living Earth: Integrating Biology and Earth Science
- Chemistry in the Earth System: Integrating Chemistry and Earth Science
- Physics of the Universe: Integrating Physics and Earth & Space Science

This model has its origin with the Modified Science Domains model presented in Appendix K of the NGSS. The choice of which ESS PEs would be included with biology, chemistry, and physics courses was based on their conceptual fit. Individual districts can integrate PEs between courses differently as long as they strive to ensure that all students meet all the standards.

Organization Within Courses

The PEs are the expected outcomes resulting from a sequence of Instructional Segments (IS) that reinforce one another as students develop the underlying knowledge of each topic. Individual PEs should not be used to develop individual lessons or activities, as they are insufficient to specify the full organization of a coherent curriculum. Rather, a bundle of selected PEs provides the breadth and depth required to address the key content ideas that students need. PEs within each course in this document are therefore bundled into instructional segments, and an effort is made to provide an expanded description of the science concepts indicated in the Disciplinary Core Ideas (DCIs) that underlie the specific set of PEs. Furthermore, the Clarification Statements and Assessment Boundaries associated with the PEs in the bundle were used to suggest student investigations aligned with the vision of three-dimensional learning: students engage in Science and Engineering Practices (SEPs) to learn DCIs that are understood better when linked together by Crosscutting Concepts (CCCs). The SEPs, DCIs, and CCCs grow in sophistication and complexity throughout the K–12 sequence. While this chapter calls out examples of the three dimensions in the text using color coding, each element should be interpreted with this grade-appropriate complexity in mind (Appendix 1 of this *Framework* clarifies the expectations at each grade span in the developmental progression).

This *CA Science Framework* provides examples and suggestions, it does not dictate requirements. The selections of PEs in each IS bundle presented in this chapter are only one example of the way PEs could be coherently organized. There are a variety of possible alternative paths and different interplays among overarching themes identified in each IS bundle. Educators should consider their local context as they reflect upon these examples. Instructional sequences are most effective when they are designed to meet the need of the specific students that will be participating in them.

The teaching of science and engineering content should be integrated with the teaching of the practices of scientists and engineers. It is through the integration of content and practices "that science begins to make sense and allows students to apply the material" (NGSS Lead States 2013c). The CA NGSS encourage teachers and students to engage with specific topics in depth, emphasizing critical thinking along with primary investigations such as in the context of case-studies.

Essential Shifts in the CA NGSS

A cursory review of the CA NGSS PEs and the 1998 California Science Standards reveals a significant change in emphasis. With the exception of the Investigation and Experimentation standards, all of the standards in the 1998 Science Standards start with the phrase “Students will know…” By contrast, the performance expectations of the CA NGSS emphasize higher level reasoning through phrases directly linked to the eight SEPs such as: “plan and conduct…”, “develop models…”, “communicate…”, “support the claim…” etc. Although the number of PEs in the CA NGSS is smaller than the number of standards in the 1998 Science Standards, they require a deeper understanding. It is critical that teachers look at the verbs embedded in each PE to understand what students are expected to do. It is no longer sufficient for students to simply “know” facts about science, they need to be able apply science and engineering practices to uncover and elucidate CCCs that have applications across many DCIs. In addition to this *CA Science Framework*, the NGSS Evidence Statements offer a concise overview of the pieces that students must know and be able to do in order to meet the PEs.

All Standards, All Students

The PEs of the CA NGSS for the high school level are the assessable statements of what *all* students should know and be able to do by the end of twelfth grade. In other words, the PEs represent the minimal assessable standards for which all high school students should be held accountable. Each of the PEs have “assessment boundaries” to guide those who construct standardized assessments. Thus, the PEs set a minimum goal, and high school science teachers should include additional expectations as appropriate for the goals of their courses. Teachers should pay close attention to the

DCIs, SEPs, and CCCs and develop each to the depth appropriate for the goals of their class using the resources in the NGSS Appendices.

Course Sequencing Discussion

California's high schools operate largely under local control. As such, course offerings and the order courses are offered for high school science are district decisions. As a result, this framework prescribes neither the courses to be offered nor the order in which they are offered. Instead, districts may consider multiple course sequences. The proposed Every Science, Every Year integrated model has a set sequence but the four-course discipline specific and three-course integrated Earth and space science models do not.

As decision makers, you have several factors to consider when deciding what will best meet your students' needs. Try not to let tradition and staffing be the only factors you consider as you make these choices. Since students learn the same eight SEPs and seven CCCs in all science classes, we are focusing on DCIs in this discussion.

The order in which high school science courses have traditionally been offered, Biology – Chemistry – Physics, has been in place for more than 100 years since the Committee of Ten first met, and may not make the most sense in our 21st century world. As you and your colleagues decide among the twenty four permutations for course sequence in the four-course model and six for the three-course model you need to be thoughtful about your choices and consider carefully the implications of the selected sequence. Strong arguments can be made for any of the sequences.

The questions and prompts below are meant to help your team with the decision.

- Is your goal to get students to take more science and science, technology, engineering and math (STEM) classes? If so, consider placing the most engaging and exciting classes as the first courses in the sequence. That may recruit more students into STEM and science classes (and possible STEM related careers and college majors).
- What course(s) are viewed as most important to your community? Put those classes first because some percentage of your students will take the minimum requirements for graduation.
- How many science classes are students in your district required to take in order to graduate? How many science classes do students in your school typically take? What science concepts and ideas do you want to be sure that all students have if they do not take the full scope of NGSS? These questions all have implications for choosing which classes (and ideas) come earliest.
- What science ideas do you think juniors and seniors are more developmentally ready to learn than freshmen and sophomores?
- What concepts and ideas do you think are more concrete so should be placed earlier in the sequence, with more abstract ideas coming later in the learning process?
- As you consider individual discipline focused classes, look at the Performance Expectations. Are there PEs from other disciplines that should be mastered for students to be successful in your particular course? If so, that has implications for sequencing.

The decision you are being asked to make is nontrivial. We urge you to spend time on the decision. Ultimately, your department/district needs to determine a two-, three- or four-year sequence of courses offerings. Whichever course sequence you select needs to consider the learning that takes place in earlier classes that will support and impact learning that comes later. The purpose of science classes is not merely to prepare students for other courses, but they are interconnected and disciplines overlap (think about those crosscutting concepts which underpin all of science). Ideas and concepts learned in one content area come into play when learning a new science discipline. These should be considered as you determine what order to place courses.

Living Earth Early or Late in the Sequence?

Biology has a better track record of interesting girls in science (AAUW 2010; Baram-Tsabari and Yarden 2011), some teachers are more comfortable with its earlier placement in the sequence, and kids are generally interested in themselves, so a course that helps them understand themselves could be a good starting point. However, modern biology requires understanding and applying chemistry and physics–much of biology today explores and explains things at the molecular or cellular level. How could topics in a high school biology course be taught differently if chemistry, for example, were taken prior to biology as opposed to afterwards?

Chemistry in the Earth System Early or Late in the Sequence?

As mentioned above, modern biology is heavily influenced by chemistry. Having chemistry prior to biology may be instructionally efficient. For example, concepts already studied in a chemistry class should require less emphasis and subsequently less time leaving room for more in-depth biology concepts. On the other hand, chemistry is rather abstract, dealing with phenomena unseen to the naked eye and frequently not intuitive to students. Knowing your students and community will help you decide if they can handle the more abstract science ideas earlier in their academic career. An understanding of physics prior to chemistry could help students better understand atomic structure, electron shells and orbitals, and bonding. Just as comfort with mathematics is an argument used for determining where physics should be offered, it can be argued that chemistry also requires a level of mathematical competence.

Physics of the Universe Early or Late in the Sequence?

Physics has traditionally been offered late in the sequence to a small population of students (it tends to be an elective course with most students electing not to take it). Many argue physics later in the course sequence allows concepts to be introduced through a more mathematically rigorous lens. Others argue physics earlier in the sequence is approachable to students as the concepts are concrete and relate to students' everyday life. Physics prior to chemistry means students bring an understanding of the mechanisms for much of the physical world to their studies. Physics after chemistry allows the opportunity to revisit ideas learned earlier. Physics early in the sequence, taken by all students, might attract more students to pursue the physical sciences – especially girls and underrepresented populations who traditionally avoid the physical sciences (Institute of Physics 2006).

Credential Information

The California Commission on Teacher Credentialing authorizes the majority of high school science teachers to teach courses that integrate the sciences across content areas. (See the California Commission on Teacher Credentialing, Specialized Single Subject Science Credentials and Alignment with the CA NGSS at http://www.ctc.ca.gov/commission/agendas/2014-08/2014-08-4C.pdf.) This includes course models that integrate Earth and Space Science with the domains of Biology, Chemistry, or Physics. While many teachers will need additional professional development, their understanding of the SEPs and CCCs should provide them with a firm foundation to teach courses in this sequence. For specific information, contact the California Commission on Teacher Credentialing at http://www.ctc.ca.gov for questions about authorization to teach integrated courses.

Physics of the Universe:

Integrating Physics and Earth & Space Sciences

Introduction

Physical processes govern everything in the Universe. Geoscientists require a strong background in the laws of physics in order to interpret processes that shape the Earth **system [CCC-4]**, and physicists benefit from applying their **models [SEP-2]** in a range of contexts. Forces of moving water push tiny particles of sand along beds of rivers, sometimes hard enough that they collide with the rocks with such force that a piece of the river bed breaks off. Over time, the Grand Canyon forms. Gravity pulls constantly on rocks at the surface of the Earth, and sometimes the frictional forces resisting movement falter. A landslide crashes down a canyon, destroying everything in its path. The nuclei of atoms thousands of miles below the surface that have remained stable for millions of years spontaneously explode apart, releasing massive amounts of **energy [CCC-5]** and heating up the surrounding rock. A geyser of hot steam erupts in California, releasing some of this excess heat to the surface. In each case, an Earth or space scientist is studying the physics of the situation, perhaps using a computer model to fast forward millions of years of **energy [CCC-5]** transfer to **explain [SEP-6]** what we see on Earth today. Alongside this scientist is a team of engineers, hoping to use this understanding to design and test solutions to many of society’s problems from natural hazards to global warming, or to minimize our impact on the natural world.

Physics teachers may not have a strong Earth science background. While it is true that there may be details and historical background that are new, the physical processes are not. The laws of physics are universal. In fact, Earth and space science applications are excellent motivations to the study of physical laws. A classic example is waves, a topic with such universal importance that Next Generation Science Standards for California Public Schools, Grades Kindergarten Through Grade Twelve (CA NGSS) devotes an entire set of Disciplinary Core Ideas (DCIs) in physical science to them. With such significance, it seems unfortunate that the most common classroom application of them is a string held between two people. While it is indeed elegant that such a simple demo can capture such a rich process, it is hard to claim that this demonstration is truly exciting or invokes great curiosity. Earthquakes, however, are all about waves and students are filled with questions motivated by personal relevance in California. Earthquakes can be visualized with real time data downloaded from around the world, or with accelerometers built into nearly every cell phone. Frequency, period, and amplitude are all there on a seismogram, ready to be interpreted. Earth science can be a door into physics.

Even a physics teacher that is enthusiastic about this integration in principle may still feel apprehensive about teaching a course that deals with a discipline they may never have studied. Research on self-efficacy shows that a teacher that is not confident will not teach as effectively, often reverting to tasks with low cognitive demand rather than the rich three-dimensional learning expected by the CA NGSS. Districts should be mindful and be sure to allocate resources to professional development and collaborative planning time so that teachers can learn from one another. No matter what resources are allocated, teachers will still have to choose how to react to the **change [CCC-7]**. Science teachers, as a general rule, became science teachers because they love learning about science. Teachers can try to approach this course with an appreciation for the opportunity to learn about a new science alongside students. They can be beacons of curiosity and inquiry in their classrooms. A teacher asking questions and seeking answers is a much better role model than a teacher that appears to know everything.

Purpose and Limitations of this Example Course

The CA NGSS do not specify which phenomena to explore or the order to address topics because phenomena need to be relevant to the students that live in each community and should flow in an authentic manner. This chapter illustrates one possible set of phenomena that will help students achieve the CA NGSS Performance Expectations (PEs). Many of the phenomena selected illustrate California's Environmental Principles and Concepts (EP&Cs), which are an essential part of the CA NGSS (see chapter 1 of this *CA Science Framework*). However, the phenomena chosen for this statewide document will not be ideal for every classroom in a state as large and diverse as California. Teachers are therefore encouraged to select phenomena that will engage their students and use this chapter's examples as inspiration for designing their own instructional sequence. For example, the course could be restructured around contemporary issues of health or ecosystem change faced by a local community.

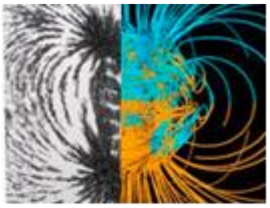
This example course is divided into instructional segments (IS) centered on questions about observations of a specific phenomenon. Different phenomena require different amounts of classroom investigative time to explore and understand, so each IS should take a different fraction of the school year. As students achieve the PEs within the IS, they uncover DCIs from Physical Science, Earth and space science, and engineering. Students engage in multiple practices in each IS, not only those explicitly indicated in the PEs. Students also focus on one or two **Crosscutting Concepts (CCCs)** as tools to make sense of their observations and investigations; the CCCs are recurring themes in all disciplines of science and engineering and help tie these seemingly disparate fields together.

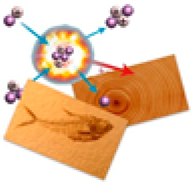
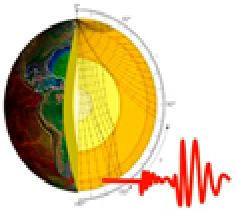
This chapter clarifies the general level of understanding required to meet each PE, but the exact depth of understanding expected of students depends on this course's place in the overall high school sequence. Teachers could modify the content and complexity so that the course serves as a basic freshman introduction to science, serves as a senior capstone that integrates and applies science learning from all previous science courses, or aligns with the expectations of advanced placement (AP) or international baccalaureate (IB) curriculum.

Example Course Mapping for an Integrated Physics and Earth and Space Science Course

The sequence of this example course (table 7.6) is based on a specific storyline about renewable **energy [CCC-5]** (figure 7.43). Both physical science (PS) and ESS DCIs emphasize how discoveries in their discipline influence society, but the two differ in which aspects of society they focus upon. Physical science emphasizes society's use of technology while Earth and space science emphasizes humanity's impact on natural **systems [CCC-4]** and the other way around (issues defined in California's Environmental Principles and Concepts, or EP&Cs). A major emphasis in the first several IS of this course is one societally relevant topic where these two disciplinary focuses intersect: electricity production. The main engineering design challenges relate to designing, building, evaluating, and refining **systems [CCC-4]** for electricity generation and considering the environmental impacts of each method on the different components of Earth's **system [CCC-4]**. The theme is not all-encompassing, as many of the PE's pertain to core ideas that are disjointed from renewable **energy [CCC-5]**.

Table 7.6. Overview of Instructional Segments for High School Physics of the Universe

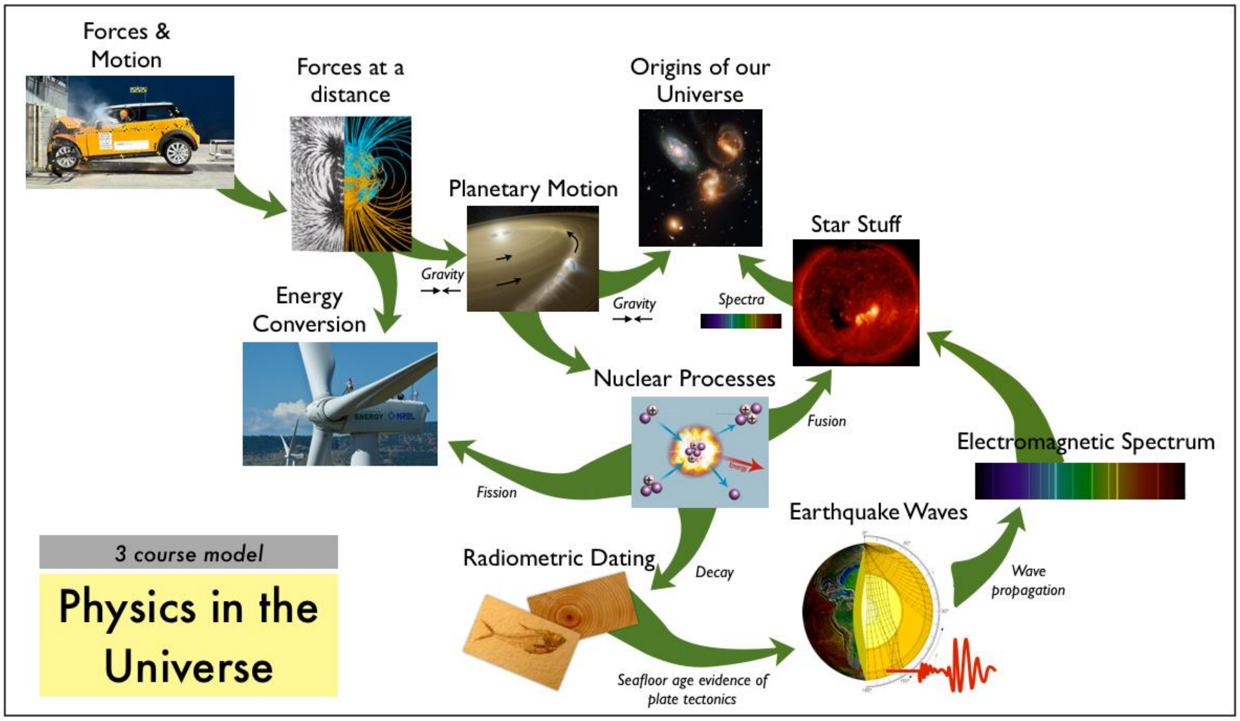
	**1** Forces and Motion	Students make predictions using Newton's Laws. Students mathematically describe how changes in motion relate to forces. They investigate collisions in Earth's crust and in an engineering challenge.
	**2** Forces at a Distance	Students investigate gravitational and electromagnetic forces and describe them mathematically. They predict the motion of orbiting objects in the solar system. They link the macroscopic properties of materials to microscopic electromagnetic attractions.

	**3** Energy Conversion	Students track energy transfer and conversion through different stages of power plants. They evaluate different power plant technologies. They investigate electromagnetism to create models of how generators work and obtain and communicate information about how solar photovoltaic systems operate. They design and test their own energy conversion devices.
	**4** Nuclear Processes	Students develop a model of the internal structure of atoms and then extend it to include the processes of fission, fusion, and radioactive decay. They apply this model to understanding nuclear power and radiometric dating. They use evidence from rock ages to reconstruct the history of the Earth and processes that shape its surface.
	**5** Waves and Electro-magnetic Radiation	Students make mathematical models of waves and apply them to seismic waves traveling through the Earth. They obtain and communicate information about other interactions between waves and matter with a particular focus on electromagnetic waves. They obtain, evaluate, and communicate information about health hazards associated with electromagnetic waves. They use models of wave behavior to explain information transfer using waves and the wave-particle duality.

	**6** Stars and the Origin of the Universe	Students apply their model of nuclear fusion to trace the flow of energy from the Sun’s core to Earth. They use evidence from the spectra of stars and galaxies to determine the composition of stars and construct an explanation of the origin of the Universe.

Sources: National Highway Traffic Safety Administration2016; Black and Davis 1913, 242, fig. 200; NASA 2003a; Leaflet 2004; Wikimedia Commons 2011; Sorenson 2012; Jordan 2010; National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2008b; Ezekowitz 2008; NASA, ESA, and the Hubble SM4 ERO Team 2009.

Figure 7.43. Conceptual Flow of Instructional Segments in Example High School Physics of the Universe Course



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Physics of the Universe – Instructional Segment 1: Forces and Motion

What does a mountain peak have in common with a pickup truck (figure 7.44)? If the vehicle is involved in a crash, its hood will crumple and bend under the force of the collision. Mountain ranges, like the Himalayas, are shortened and pushed upwards just like the hood of a crashed car. Even though the two processes occur at very different **scales [CCC-3]**, they are both governed by Newton's Laws.

Physics of the Universe – Instructional Segment 1: Forces and Motion
Guiding Questions • How can Newton's Laws be used to explain how and why things move? • How can mathematical models of Newton's Laws be used to test and improve engineering designs?
Performance Expectations
Students who demonstrate understanding can: HS-PS2-1. Analyze data to support the claim that Newton's second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration. **[Clarification Statement: Examples of data could include tables or graphs of position or velocity as a function of time for objects subject to a net unbalanced force, such as a falling object, an object rolling down a ramp, or a moving object being pulled by a constant force.] [Assessment Boundary: Assessment is limited to one-dimensional motion and to macroscopic objects moving at non-relativistic speeds.]** HS-PS2-2. Use mathematical representations to support the claim that the total momentum of a system of objects is conserved when there is no net force on the system. **[Clarification Statement: Emphasis is on the quantitative conservation of momentum in interactions and the qualitative meaning of this principle.] [Assessment Boundary: Assessment is limited to**

systems of two macroscopic bodies moving in one dimension.]

HS-PS2-3. Apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision.* **[Clarification Statement: Examples of evaluation and refinement could include determining the success of the device at protecting an object from damage and modifying the design to improve it. Examples of a device could include a football helmet or a parachute.] [Assessment Boundary: Assessment is limited to qualitative evaluations and/or algebraic manipulations.]**

HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

HS-ETS1-2. Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

*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-4] Analyzing and Interpreting Data** **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-7] Engaging in Argument from Evidence**	**PS2.A : Forces and Motion** **ETS1.A: Defining and Delimiting Engineering Problems** **ETS1.B: Developing Possible Solutions**	**[CCC-2] Cause and Effect** **[CCC-4] System and System Models** **[CCC-6] Structure and Function**

Highlighted California Environmental Principles & Concepts:

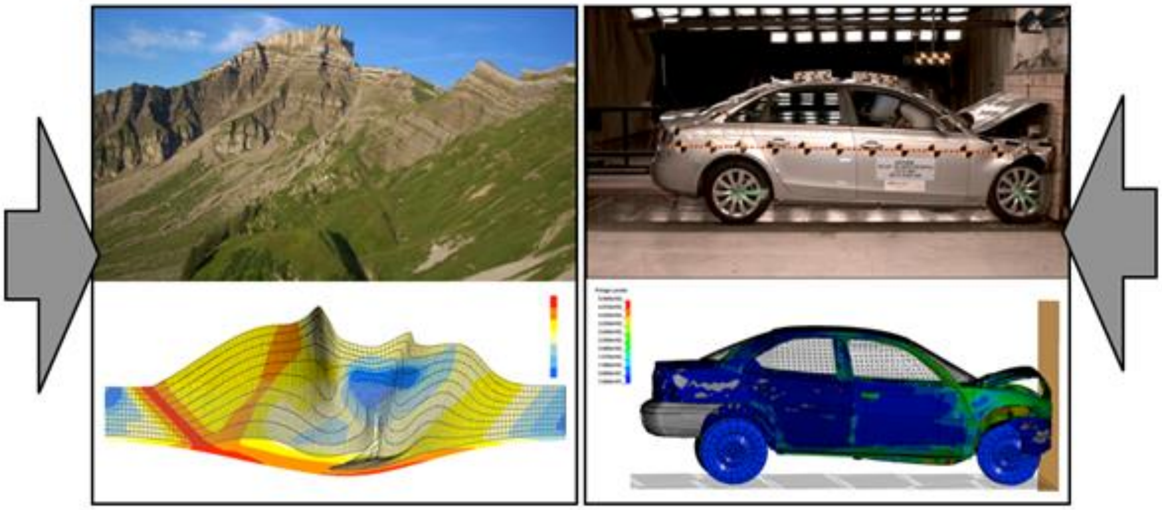
Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes.

CA CCSS Math Connections: N-Q.1-3; A-SSE.1a-b, 3a-c; A-CED.1,2,4; F-IF.7.a-e; S-ID.1; MP.2; MP.4

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

CA CCSS ELA/Literacy Connections: SL.11-12.4,5; RST.11-12.1,7,8, WHST.9-12.9

Figure 7.44. Collisions Occur in a Variety of Contexts



Mountains and car crashes involve collisions whose movement and forces can be modeled in computer simulations (bottom). Sources: Cinedoku Vorarlberg 2009; National Highway Traffic Safety Administration2016; Willett 1999; Livermore Software Technology Corporation 2017.

Table 7.7. Newton's Laws of Motion

1st Law "Law of Inertia"	Every object in a state of uniform motion tends to remain in that state of motion unless it is subjected to an unbalanced external force.
2nd Law "Definition of Force"	$F = ma$. An object's acceleration, a, depends on its mass, m, and the applied force, F.
3rd Law "Law of Reciprocity"	"For every action, there is an equal and opposite reaction." When one body exerts a force on a second body, the second body simultaneously exerts a force equal in magnitude and opposite in direction on the first body

Opportunities for ELA/ELD Connections

As a foundation for the study of physics, have students create "mini-lessons" on Newton's Laws of Motion to present to the class. Each team or group of students use at least two different sources to research a law of motion for a visual presentation to the class. The presentation should include a general description/definition of the law plus an example demonstrating the application of the principle. Visual presentations make strategic use of digital media to enhance findings, reasoning, evidence, and add interest.

CA CCSS ELA/Literacy Standards: RST.9–12.2, 7; WHST. 9–12.6, 7, 8; SL.9–12.5

CA ELD Standards: ELD.PI. 9–12.6, 9

Newton's Laws (table 7.7) provide a basis for understanding forces and motion and, therefore, serve as a foundation for a study of physics. Engineers and scientists apply Newton's Laws mathematically or with **computational models [SEP-2]** to predict the motion of objects. These calculations (such as depicted in the bottom panels of figure 7.44) enable applications as diverse as building safer automobiles and providing more reliable forecasts of earthquake hazard. Applying Newton's laws becomes quite complicated when considering the forces within deforming bodies like in figure 7.44, but these simple laws lie at the heart of even the most sophisticated computer simulations.

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CA CCSS ELA/Literacy Standards: RST.9–12.2, 7; WHST. 9–12.6, 7, 8; SL.9–12.5

CA ELD Standards: ELD.PI. 9–12.6, 9

In the middle grades, students investigated forces to establish a relationship between force, mass, and changes in motion (MS-PS2-2) and designed solutions to minimize the impact of a collision (MS-PS2-1). These experiences form the basis of a solid conceptual model of Newton's laws. Now, they are ready to **extend these models [SEP-2]** using **mathematical thinking [SEP-5]** so that they can use their models to predict precise outcomes. This process begins with mathematical descriptions of motion.

HS-PS2-1 requires students to “analyze data to support the claim that Newton’s second law of motion describes the mathematical relationship among the net force on a macroscopic object, its mass, and its acceleration.” Before jumping into quantitative calculations, teachers should help students engage with their preconceptions about forces and motion through conceptual challenges. Teachers can administer the Force Concept Inventory (Hestenes 1998) to assess students’ knowledge at the beginning of the course. Guided inquiry tutorials (see University of Maryland Physics Education Research Group, Tutorials in Physics Sense-Making at http://umdperg.pbworks.com/w/page/10511239/Tutorials%20in%20Physics%20Sense-Making) help students refine their conceptual models and are specifically designed for students to confront misconceptions. With these foundations, students **analyze and interpret [SEP-4]** tables or graphs of position or velocity as a function of time for objects subjected to a constant, net unbalanced force and compare their observations to predictions from the mathematical model (*HS-PS2-1*). Given the force and the mass, students learn to calculate the acceleration of an object. Given the mass and the acceleration, students should be able to calculate the net force on the object. Accordingly, students should be able to analyze simple free-body diagrams to calculate the net forces on known masses and, subsequently, determine their acceleration. In each of these cases, the clarification statement for *HS-PS2-1* states that students should be examining situations where the force remains constant during the interaction. Gravity is the most consistent way to apply a constant force, so the most consistent results will come from analyzing objects moving down ramps or falling. Computer simulations and digital video analysis tools generate graphs of position vs. time, speed vs. time and acceleration vs. time, providing an opportunity to visualize, analyze and model motion.

The standard formulas of velocity, acceleration, and Newton’s second law are all mathematical **models [SEP-2]**. In the CA NGSS, students should be able to use models to make predictions. Curriculum should therefore provide students opportunities to not only perform calculations, but to test them out using hands-on activities and computer simulations.

Engineering Connection: Testing Material Strength

Newton’s second law can also be used to test the strength of different materials for a design challenge. A satellite must withstand vibrations from a rocket launch, a hospital must withstand earthquake shaking, and a child’s toy must be able to withstand being sat upon by a toddler. In many of these cases, it is not practical to do iterative testing on the actual objects (they cannot build various trials of a hospital and have each of them fall down – each one takes years and cost millions of dollars to complete). Instead, engineers do calculations to test their designs before investing the time and materials of actually building a prototype. In the classroom, students could determine the maximum force a toothpick can withstand before it snaps or a toilet paper tube before it buckles. They do this by placing heavy objects on top of the test material and measuring the amount of mass that **causes [CCC-2]** the material to break. Since the acceleration of gravity is constant, the force can be calculated using the mathematical model $W = mg$ (a special case of $F = ma$ where W is the force of the object’s weight, m is mass, and g is the constant of gravitational acceleration). By comparing this force to calculations of the expected force on impact during a design challenge, they can make informed decisions about materials. Engineers perform similar calculations to provide evidence that their design will withstand the expected forces. They often use computer simulations like in figure 7.44 to perform these calculations.

Students extend their study of forces and motion to include collisions and the concept of momentum. The law of conservation of linear momentum states that for a collision occurring between object one and object two in an isolated **system [CCC-4]**, the total momentum of the two objects before the collision is equal to the total momentum of the two objects after the collision. Again, students will use **mathematical representations [SEP-5]** of these systems as **models [SEP-2]**. They should be able to apply these models to a range of scenarios.

The assessment boundaries for HS-PS2-1 and HS-PS2-2 are limited to one-dimensional **systems [CCC-4]** with constant forces. Most everyday interactions, however, are more complicated and involve complex, three-dimensional systems in which forces and accelerations change. Thus, the motion of such things as a swinging trapeze artist, the crushing of a car door during a side impact, or the ground shaking during an earthquake can be broken down and analyzed qualitatively in terms of the three-dimensional forces acting on the objects at each moment during the motion. Computational **models [SEP-2]** employ this exact strategy, using Newton’s laws to calculate changes in motion over a series of short, successive time increments. The snapshot is one example of a complex problem in Earth science motivated by rich context and then addressed using tools appropriate for the high school level in the CA NGSS.

Physics of the Universe Snapshot 7.11: Applying Newton's Laws to the Earth

Mr. H runs an efficient technology-enhanced classroom where he is helping students become self-starters on engaging individual projects. After a few weeks investigating Newton's Laws through laboratory **data analysis [SEP-4]** (*HS-PS2-1*), direct instruction, guided practice, and homework problem sets, Mr. H. wants his students to be able to relate them to Earth processes.

Anchoring phenomenon: Many ocean trenches, oceanic ridges, mountain ranges, valleys, and plateaus on Earth are long and relatively straight.

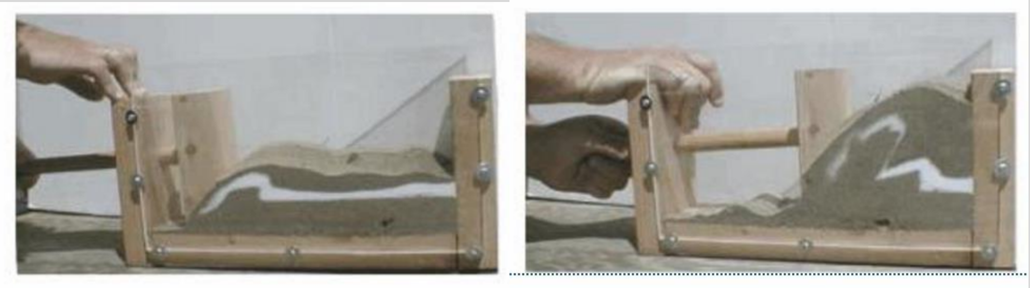
As Mr. H.'s students enter the room, they open the class website on their mobile devices and find today's agenda. Each group of three students is assigned to investigate and characterize one of the following land and sea-floor features with a virtual globe, map, and geographical information program such as Google Earth: trenches (Mariana, Aleutian, Puerto Rico, Japan), oceanic ridges (Mid-Atlantic, East Pacific, Nazca, Mid-Indian), seamounts (Loihi, Davidson, Tamu Massif, Banua Wuhu), mountain ranges (Himalaya, Sierra Nevada, Rocky Mountains, Alps), valleys (California Central Valley, Ethiopian Rift, Yosemite Valley, Rhone), or plateaus (Kukenan Tepui, Monte Roraima, Table Mountain, Auyantepui). As the opening bell rings, students are already actively searching their geomorphic features. Mr. H. uses remote desktop to freeze their devices so he can clarify the instructions printed on the agenda webpage. Each team is to develop a tour-guide script that one of their members will read as they introduce their geomorphic feature to the class. Each group is to create a narrated animated tour in which they provide voiceovers, and descriptive pop-up balloons, as they "fly" their audience around the globe in a video-like experience. Each animated "fly-by" or "float-by" tour must include a description of the constructive forces (such as volcanism and tectonic movements) and destructive mechanisms (such as weathering, landslides, and coastal erosion) that have shaped their feature (*HS-ESS2-1*). Students work throughout the period, integrating their knowledge of plate motions and surface processes with the features they observe. Students are required to make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in their presentations to enhance understanding of findings, reasoning, and evidence and to add interest, thereby meeting *CA CCSS SL.11-12.*

The following day, students proudly present their fly-by videos, providing the class with an introduction to key oceanic and continental geomorphic features. Following the video presentations, Mr. H. asks students to describe how Newton's Laws helps explain the formation of such features. Students type their responses into an online form that allows Mr. H to monitor their thinking in real-time. It soon becomes clear that although his students seem to have a good grasp of Newton's laws as measured by a traditional assessment, and although they seem to have a good understanding of key geomorphic features, they seem to be unable to apply Newton's Laws to explain the formation of such features.

Investigative phenomenon: Layers of sand in a squeeze box deform as a plunger presses against one end.

Mr. H. proceeds with an interactive lecture on the concept of geological stress (pressure), the ratio of force per unit area. Although pressure is easy to conceptualize and measure using the simple, homogenous, discrete objects commonly used in physics investigations, it is much more difficult to understand when discussing complex, heterogeneous, continuous objects such as the Earth's crust. To help students visualize the application of Newton's Laws in geological systems, Mr. H. presents a squeeze box with a screw mechanism (figure 7.45).

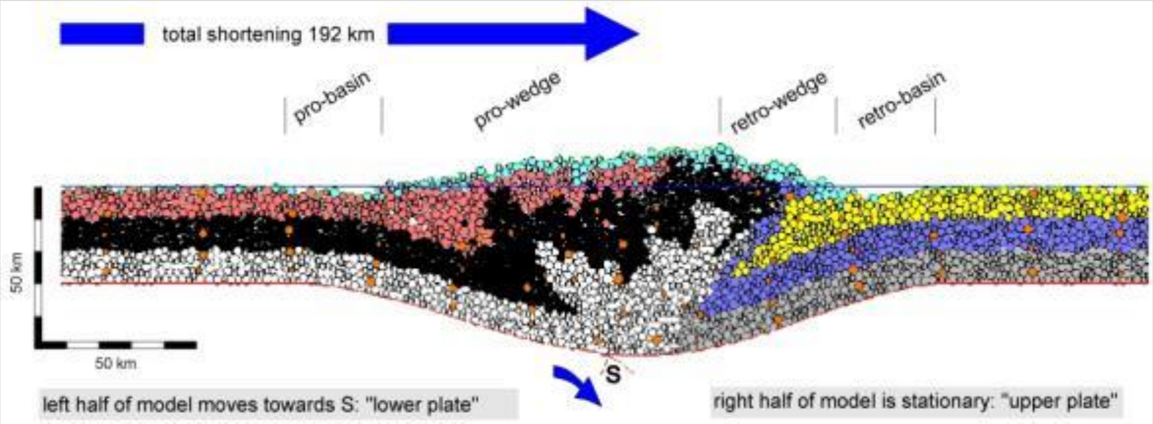
Figure 7.45: Physical Model of Forces Deforming Layers in a Sandbox



Source: Exploratorium 2000

Layers of dark and light sand are placed in alternating horizontal layers in the box and pressure is applied with a screw mechanism. As the crank turns, layers deform, simulating geological folding and mountain building. Unlike other physics problems the students have considered with rigid objects, the sand is clearly not rigid. Scientists often break down complex problems like this into much smaller pieces, where the smaller pieces each behave like a rigid body. Mr. H shows an example where scientists use this sort of **computational thinking [SEP-5]** using computer simulations called 'discrete element analysis.' (figure 7.46)

Figure 7.46: Computer Model of Layers Deforming During Continental Collision



Source: Handy 2006

Mr. H asks students to work in pairs to label the forces acting on a small section of sand near the middle of the model. Students upload photos of their diagrams to the class webpage so that everyone can see their peers' work. Mr. H selects two student diagrams to show side-by-side and asks the class to identify the differences (figure 7.47). Most of the students had correctly identified the force related to the crank pushing on one side, but a substantial fraction of them forget to include the force of the opposing wall. Mr. H asks students to consider the vector sum of the forces to make sure it points in the same direction as the change in motion.

Figure 7.47: Example Student Diagrams

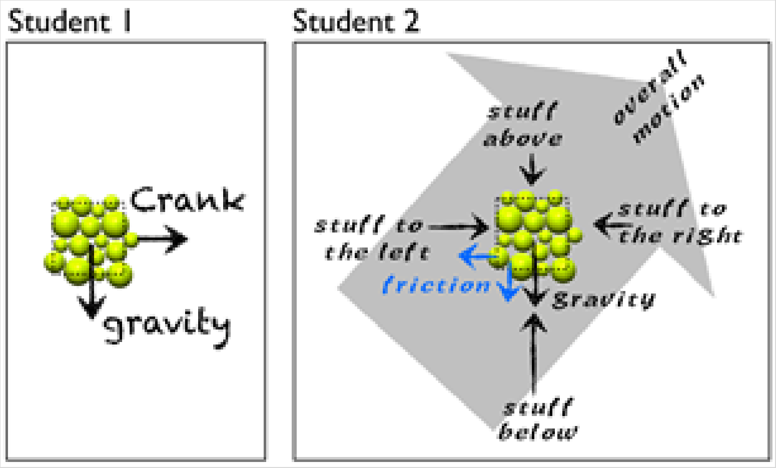


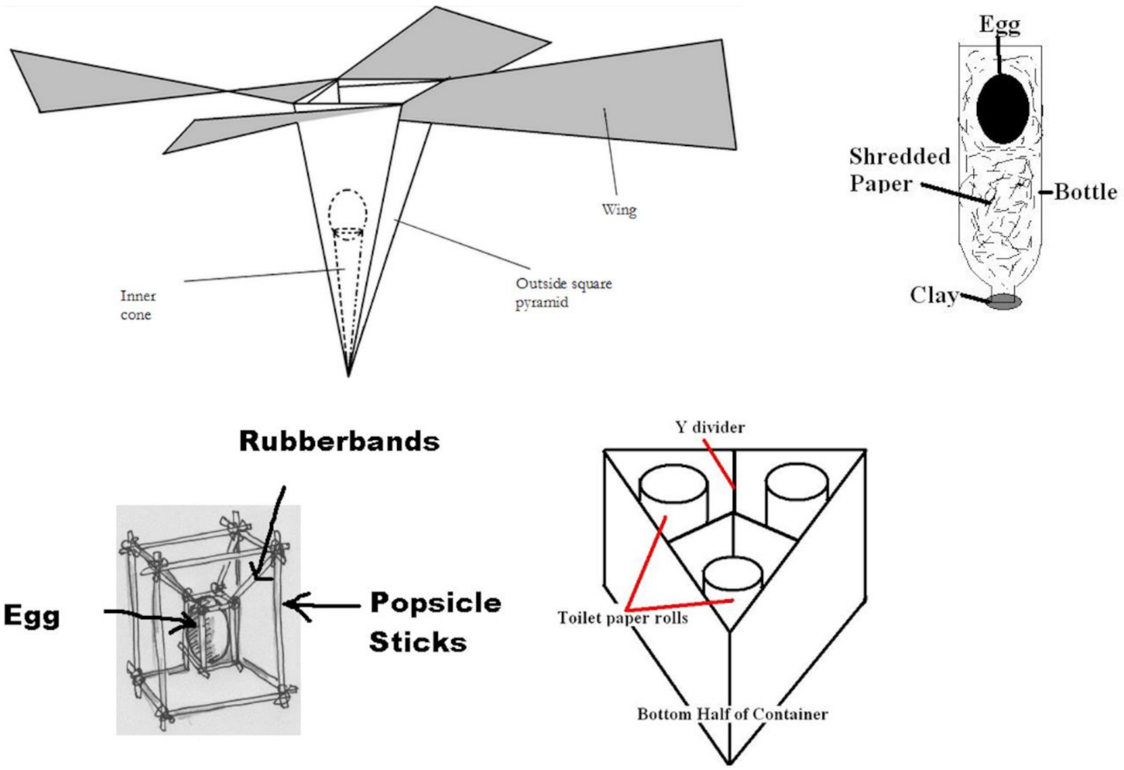
Diagram by M. d'Alessio

Mr. H next asks students how Newton's second law (*F*=*ma*) applies to this situation using the online student response form. This time, many students mention that force (applied through the screw) causes the mass of the individual particles (sand) to accelerate as evidenced by the movement of layers within the box. Mr. H tells the students that there is some truth to that statement, but he disagrees that this explanation describes most of the motion within the system. He challenges his students to identify the evidence that he is basing his **argument [SEP-7]** upon. They are confused at first, but Mr. H walks around as teams of students discuss his statement. He asks them leading questions, such as “how would you describe the velocity of the wall?” Each team eventually realizes that once it started moving, the wall continued to move at a constant velocity and was therefore not accelerating. A large fraction of the sand in the model moves constantly but does not deform, so it too does not accelerate. At any given time, only a small fraction of the model is accelerating. The same thing happens in the real world. Mr. H shows observations from precise GPS measurements that reveal most plates move at constant rates in constant directions for decades (i.e., no acceleration). There are clearly forces being applied to the **system [CCC-4]**, so how come it doesn’t accelerate despite the constant force applied on the edges? Some students recognize friction as being important as the grains of sand slide past one another. They reason that friction or other forces within the system must balance the external forces. Earth scientists studying plate tectonics consider both the driving forces that push and pull the plates (related to gravity and convective processes in Earth’s interior) as well as friction along the boundaries of plates (including drag along the bottom), momentum transfer from collisions with other plates, and the forces that arise from energy dissipation from friction within materials (often called ‘plastic deformation’). Even today, scientists are still trying to find ways to measure or estimate the strength of these forces to determine which ones are ‘most important’ for causing the plates to move and deform. Beyond plate motions, plastic deformation is an important part of the energy balance of devices that minimize force during collisions such as vehicle crumple zones (related to *HS-PS2-3).*

Engineering Connection: Collision Challenge

Equipped with a basic understanding of classical mechanics, including Newton’s three Laws of Motion and the momentum conservation principle, students should now be able to “*apply scientific and engineering ideas to design, evaluate, and refine a device that minimizes the force on a macroscopic object during a collision*”. (*HS-PS2-3*). A classic activity that meets this PE is the egg-drop contest, in which students are challenged to develop devices that protect raw eggs from breaking when dropped from significant heights (figure 7.48). In the process, students demonstrate competence with *HS-ETS1-1* where they start by considering a complex problem such as automobile collisions or sports injuries, and then they **define the problem [SEP-1]** in terms of qualitative and quantitative criteria and constraints for solutions. With teacher guidance the students can then break down the problem into smaller, more manageable problems that can be solved through engineering (*HS-ETS1-2*). The students should be encouraged to **generate multiple solutions [SEP-6]**, and to evaluate their ideas based on prioritized criteria and trade-offs (see the section on ‘Decision Matrices’ in the instructional strategies chapter of this *CA Science Framework*), taking into account cost, safety, and reliability as well as social, cultural, and environmental impacts (*HS-ETS1-3*). Students then build and test a model of their most promising idea and then modify it based on the results of the tests. Testing can include computer simulations that model how solutions function under different conditions (*HS-ETS1-4*).

Figure 7.48. Engineering Solutions to an Egg Drop Challenge

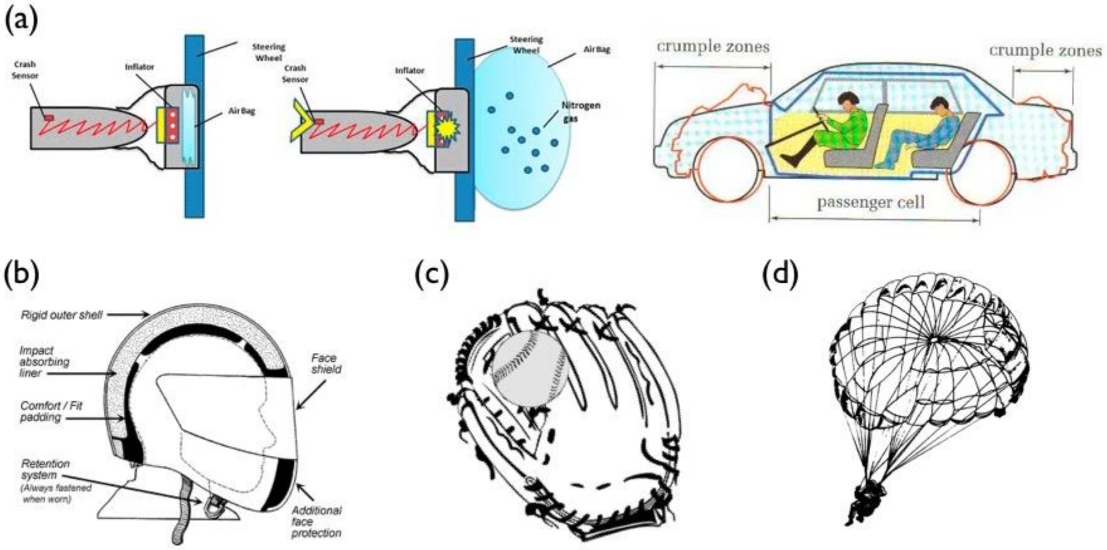


Students learn physics principles such as impulse and momentum while simultaneously learning engineering design and testing principles while designing and developing devices for challenges such as the classic egg-drop contest. Source: William R 2014; Prack n.d.; Magnotto 2011.

Throughout the process, students should **justify [SEP-7]** their design choices and revisions in terms of physics concepts, rather than using trial and error or guesswork. The engineering solutions students create are examples of **systems [CCC-4]** of interacting components. Students discover that the exact physical **structure [CCC-6]** (the arrangement of the components) can have a large impact on the function of their design. Students can draw pictorial **models [SEP-2]** showing the direction forces act and label role each piece plays in their solution.

Engagement in this activity also tests student understanding of the momentum-impulse connection: $F\Delta t = m\Delta v$, where F = *force*, t = *time*, m = *mass*, and v = *velocity.* The product of force and the time over which the force is applied is known as the impulse *(FΔt)* and is equal to the change in momentum of the object to which the force is applied (*mΔv)*. One can decrease the force necessary to bring a moving object to rest by increasing the time over which the force is applied. For example, air bags, car crumple zones, helmets, parachutes, and padded catcher's mitts (figure 7.49) reduce the potential for injury by decreasing the force necessary to bring objects to a halt by increasing the time over which such forces are applied.

Figure 7.49. Real World Engineering Applications of Momentum-Impulse Connections



The Product of force and the time over which the force is applied is known as the impulse (FΔt), and is equal to the change in momentum of the object to which the force is applied (mΔv). One can decrease the force (F) necessary to bring a moving object to rest by increasing the time (Δt) over which the force is applied, such as is accomplished by (a) an automobile air bag, (b) a helmet, (c) a baseball catcher's mitt, or (d) a parachute. Sources: Clemson University Vehicular Electronics Laboratory n.d.; Grabianowski 2008; Chandigarh Traffic Police n.d.; Clker-Free-Vector-Images 2012; Headquarters Department of the Army 2012.

Physics in the Universe - Instructional Segment 2: Forces at a Distance

IS1 introduces the concept of force as an influence that tends to change the motion of a body or produce motion or stress within a stationary body. While forces govern a wide range of interactions, the design challenge and many of the simplest applications from IS1 primarily involved interactions between objects that appeared to be physically touching. IS2 builds upon this foundation by examining gravity and electromagnetism, forces that can be modeled as fields that span space. Despite the fact that we cannot see them, we interact with these fields on a daily basis and students are already familiar with their pushes and pulls.

Physics in the Universe – Instructional Segment 2: Forces at a Distance
Guiding Questions • How can different objects interact when they are not even touching? • How do interactions between matter at the microscopic scale affect the macroscopic properties of matter that we observe? • How do satellites stay in orbit?
Performance Expectations
Students who demonstrate understanding can: HS-PS2-4 Use mathematical representations of Newton's Law of Gravitation and Coulomb's Law to describe and predict the gravitational and electrostatic forces between objects. **[Clarification Statement: Emphasis is on both quantitative and conceptual descriptions of gravitational and electric fields.] [Assessment Boundary: Assessment is limited to systems with two objects.]** HS-PS2-6 Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials.* **[Clarification Statement: Emphasis is on the attractive and repulsive**

forces that determine the functioning of the material. Examples could include why electrically conductive materials are often made of metal, flexible but durable materials are made up of long chained molecules, and pharmaceuticals are designed to interact with specific receptors.] [Assessment Boundary: Assessment is limited to provided molecular structures of specific designed materials.]

HS-ESS1-4. Use mathematical or computational representations to predict the motion of orbiting objects in the solar system. **[Clarification Statement: Emphasis is on Newtonian gravitational laws governing orbital motions, which apply to human-made satellites as well as planets and moons.] [Assessment Boundary: Mathematical representations for the gravitational attraction of bodies and Kepler’s Laws of orbital motions should not deal with more than two bodies, nor involve calculus.]**

*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**	**PS2.A: Forces and Motion** **ETS1.A: Defining and Delimiting Engineering Problems**	**[CCC-1] Patterns** **[CCC-2] Cause and Effect** **[CCC-3] Scale,**

[SEP-3] Planning and Carrying Out Investigations **[SEP-4] Analyzing and Interpreting Data** **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-7] Engaging in Argument from Evidence** **[SEP-8] Obtaining, Evaluating, and Communicating**	**ETS1.B: Developing Possible Solutions**	**Proportion, and Quantity** **[CCC-4] System and System Models** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-7] Stability and Change**

Information		
CA CCSS Math Connections: N-Q.1-3; A-SSE.1a-b, 3a-c; A-CDE.2; A-CDE.4; MP.2; MP.4		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: RST.11-12.1, WHST.9-12.2.a-e,		

At the middle grade level, students laid out a firm groundwork for studying gravitational and electromagnetic forces. They gathered **evidence [SEP-7]** that fields exist between objects and exert forces (*MS-PS2-5*), **asked questions [SEP-1]** about what causes the strength of electric and magnetic forces to vary (*MS-PS2-3*), and determined one factor that affects the strength of the gravitational force (*MS-PS2-4*). This high school IS extends those skills by providing mathematical **models [SEP-2]** of these forces. Though students' everyday experience with electric forces, magnetic forces, and gravity all seem to be independent of one another, these mathematical models will reveal some important connections between them.

Science and Engineering Practices and the History of Gravity

Although scientists have studied gravity and electromagnetism intensely for centuries, many mysteries remain concerning the nature of these forces. The CA NGSS learning progression mirrors the historical development of our understanding of gravity and orbital motion. In 1576, Danish scientist Tycho Brahe set up the world's most sophisticated astronomical observatory of its time. He methodically **investigated [SEP-3]** and recorded the motion of celestial objects across the sky. Just before he died, Brahe took on Johannes Kepler as a student who **analyzed the data [SEP-4]** to develop a simple descriptive **model [SEP-2]**. Even though his model did a superb job of predicting the motion of objects in the sky, it was incomplete because it could not explain the fundamental forces driving the motions. In late 1600s, Isaac Newton extended Kepler's model by describing the nature of gravitational forces. From his fundamental equations of gravity, Newton was able to derive Kepler's geometric laws and match the observations of Brahe. Newton is known not only for his innovative thinking, but for his ability to **communicate [SEP-8]** clearly; many 21st century physics classes still read his book, *Principia Mathematica,* to learn about his ideas. In the CA NGSS, elementary students mirror the work of Brahe, recognizing **patterns [CCC-1]** in the sky (*1-ESS1-1*, *5-ESS1-2*). At the middle grade level, students mirror the work of Kepler by *making simple* **models [SEP-2]** *that* describe how galaxies and the solar system are shaped (*MS-ESS1-2*). In high school, students add **mathematical thinking [SEP-5]** to their descriptive model (using Kepler's laws, *HS-ESS1-4*) and then finally extend their model to a full explanation with the equations of the force of gravity from Newton's model (*HS-PS2-4*).

Equations of Gravitational Force

Students should be able to use Newton's Law of Gravitation to describe and predict the gravitational attraction between two objects (HS-PS2-4). Newton's Law is expressed as $F=Gm_1m_2/r^2$, where F represents the gravitational force, m_1 and m_2 represent the masses of two interacting objects, r represents the distance (radius) between the centers of mass of these two objects, and G is the universal gravitational constant.

Opportunities for Mathematics Connection

Students should be able to "rearrange formulas to highlight a quantity of interest, using the same reasoning as in solving equations." (CA CCSSM A-CED.4). Thus, given G and any three of the variables, students should be able to apply basic algebra to **calculate [SEP-5]** the value of the remaining variable. Students are expected to make quantitative predictions using this equation, and they must also be able to understand it qualitatively (*HS-PS2-4*).

CA CCSS Math Standards: A-CDE.4

Mathematical models, such as expressed in Newton's Law of Gravitation, provide the opportunity for students to conceptualize complex physical principles using elegant equations. All mathematical **models [SEP-2]** in science are based on physical principles of relationships between **scale, proportion, and quantity [CCC-3]**. To assess understanding of such models, teachers can ask questions like, "What happens to the force of gravity if one doubles the mass?" or "What happens to the force of gravity if the distance between the centers of mass of the two objects is doubled?" In the middle grades, students argued that gravity always attracts objects together, but only had empirical evidence could not describe any mechanism for this behavior. Students can **explain [SEP-6]** why gravity is always attractive by referring to Newton's Law of Gravitation (noting that mass can never be negative, so all terms are positive).

Equations of Electrostatic Force

Working together, electricity and magnetism are a constant presence in daily life: electric motors, generators, loudspeakers, microwave ovens, computers, telephone systems, static cling, the warm glow of the Sun, maglev trains, and electric cars, to name a few.

Asking students to identify the scientific principles that engineers apply in order to design and improve such technologies provides opportunities to review prior learning and recognize the value of science in everyday life. It also opens the door to understanding the **interdependence of science, engineering, and technology [CCC about nature of science]** in which scientists aid engineers through discoveries that can be incorporated into new devices, while engineers develop new instruments for observing and measuring phenomena that help further scientific research. In the high school chemistry course, students will create a model describing how electromagnetic forces are ultimately responsible for holding atoms together in chemical bonds.

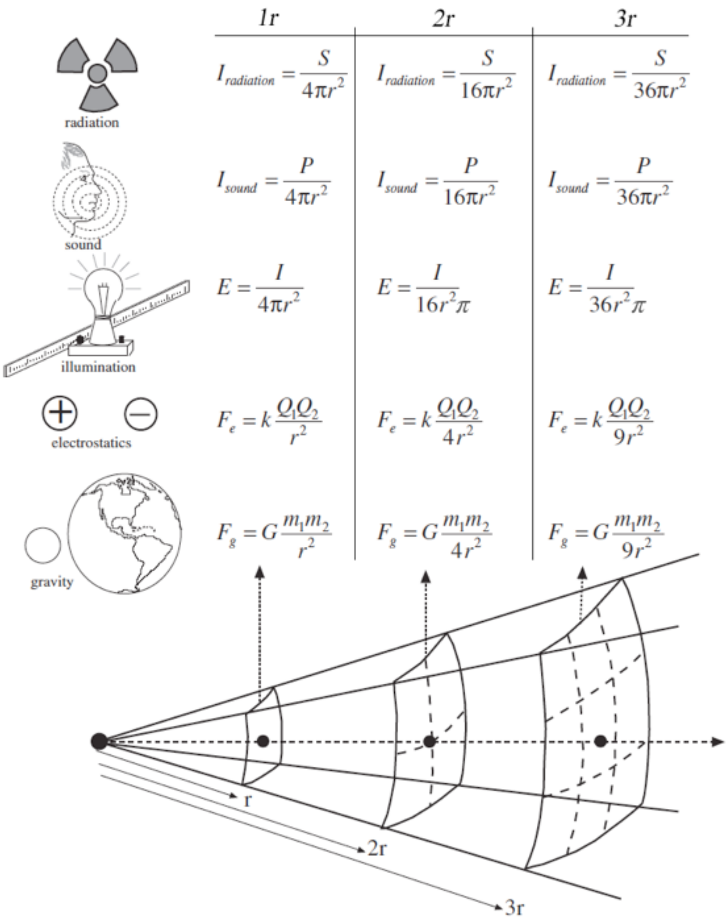
Students likely have experience with magnetic latches and are aware of static electricity, but they will need first hand experiences with electrostatic forces. Are they always attractive like gravity? Students can explore conceptual hands-on tutorials (see the University of Maryland Physics Education Research Group Tutorials in Physics

Sense-Making at http://umdperg.pbworks.com/w/page/10511239/Tutorials%20in%20Physics%20Sense-Making) and interactive simulations (see the Concord Consortium Electrostatics" at https://concord.org/stem-resources/electrostatics).

Students should be able to use the simple equation in Coulomb's Law to predict electrostatic forces between two electrically charged objects (HS-PS2-4). Coulomb's Law states: $F = k(q_1q_2)/r^2$, where F is the electrostatic force, k is the Coulomb's constant, q_1 and q_2 are the magnitudes of the charges, and r is the distance between the charges. Given k and any three of the variables, students should be able to calculate the value of the remaining variable.

Students should notice that Coulomb's Law is strikingly similar to Newton's Universal Law of Gravitation. Both forces apparently have an infinite range and are directly proportional to the magnitude of the component parts (the two masses or the two charges), and inversely proportional to the square of the distance between them. With guidance, students apply **computational and mathematical thinking [SEP-5]** to conclude that gravitational and electrostatic forces share a common geometry, radiating out as spherical shapes from their point of origin (figure 7.50).

Figure 7.50. Many Physical Processes Follow the Inverse Square Law



The intensity of radiation, sound, illumination, electrostatic interaction, and gravity vary as a function of distance (radius, *r*) from the source. Source: Herr 2008, 285.

Physics in the Universe Snapshot 7.12: Coulomb’s Law, Newton’s Gravitation, and CA CCSSM Geometry

Everyday phenomenon: Waves spread out in all directions when a rock falls into a pond.

Ms. C asks her students to imagine throwing a rock into a glassy-smooth pond. Waves emanate in all directions from the point where the rock hits the surface of the pond. As a wave moves from the point of impact, the same **energy [CCC-5]** is spread over an increasingly large area. Initially the waves are tall, but as the waves get farther from the source, they become more diffuse. What is true of the water wave along the surface of the pond is similar to what happens to any point source that spreads its influence equally in all directions. Although the water waves are confined to the surface of the water, point sources, such as radiation, sound, seismic waves, illumination, electrostatics and gravity display a similar attenuation with distance (figure 7.50).

Investigative phenomenon: Waves get weaker as you move farther from their source.

Ms. C provides students access to all the equipment in the lab and asks them to **develop a model [SEP-2]** that illustrates how intensity varies with distance. Tom and Min used a marker to color a square on a balloon and are proceeding to inflate the balloon to observe how the color of the square gets lighter as the balloon is inflated. As Joshua and Maria observe Tom and Min, they get the idea to do the same, but use their cell phones to video their balloon as it is inflated so that they will have a permanent record to share with the class. Julia and Tae realize that Joshua and Maria have a good idea, but are lacking a scale, and improve upon their design by including a ruler in the background. Ms. C subsequently asks all three teams to share their ideas, and then asks Julia and Tae to wirelessly send their movie to the data projector so the class can observe the model (CA CCSS for ELA/Literacy SL.11–12.5). Students now estimate the surface area of the balloon at three different radii (*CA CCSSM G-GMD.1*) and note how the intensity of the marker color decreases significantly with increasing radius (CA CCSSM G-GMD.5).

Applications of Gravitational Force: Planetary Motions

In order to verify that his mathematical model of gravitation was correct, Newton compared his results to observations of planetary orbits. If gravity was holding the planets in their orbits, Newton should be able to show it. He rearranged his equation in order to compare its prediction to the previous work of Johannes Kepler who used geometry to describe planetary motion. Indeed, Newton's equation simplified to match Kepler's. The focus of this section is not on deriving Kepler's Laws for elliptical orbits directly from the gravitational force, but instead on interpreting the evidence of the orbital period of different bodies in our solar system, including planets and comets. These laws form an excellent illustration of **scale, proportion, and quantity [CCC-3]**. By comparing the distance of objects away from the Sun and the time it takes them to complete one orbit, students recognize a **pattern [CCC-1]** and then use this pattern to predict orbital parameters using Kepler's Laws (HS-ESS1-4). Table shows that the ratio determined by Kepler (orbital period squared divided by orbital distance cubed) is nearly constant for objects in our solar system. Students can calculate this ratio for Earth and other planets and then make measurements of the orbital path of comets to try estimate how often they will return. The ratio is only true for objects orbiting the same body (illustrated by the dramatically different ratio for the Moon in Table), but students can use measurements of the Moon to predict the height of satellites in geosynchronous orbit (they have an orbital period of exactly one day, which allows them to always be in the same position in the sky; satellite television receives signals from these satellites), or the orbital period of the International Space Station from its height above Earth. Students can also use the more complete form of Kepler's laws to calculate the mass of distant stars using only the orbital period of newly discovered planets that orbit them.

Table 7.8. Observations of Planetary Distance and Orbital Period

Planet	Period (yr)	Average Distance (AU)	Kepler's ratio: T^2/R^3 (yr^2/AU^3)
Mercury	0.241	0.39	0.98
Venus	0.615	0.72	1.01
Earth	1	1	1.00
Mars	1.88	1.52	1.01
Jupiter	11.8	5.2	0.99
Saturn	29.5	9.54	1.00
Uranus	84	19.18	1.00
Neptune	165	30.06	1.00
Pluto	248	39.44	1.00
Halley's comet	75.3	17.8	1.00
Comet Hale Bopp	2,521	186	0.99
Moon (relative to Earth)*	0.0766	0.00257	345667*

* Kepler's ratio only works for objects orbiting around the same body. Since Moon orbits Earth, its ratio should be much different.

Engineering Connection: Computational Models of Orbit

When a company spends millions of dollars to launch a communications satellite or the government launches a new weather satellite, they employ computer models of orbital motion to make sure these investments will stay in orbit. These **models [SEP-2]** are based on the exact equations introduced in the CA NGSS high school courses. In fact, students can gain a deeper understanding of the orbital relationships and develop **computational thinking [SEP-5]** skills by interacting directly with computer models of simple two-body **systems [CCC-4]**. Even with minimal computer programming background, students could learn to interpret an existing computer program of a two-body gravitational system. They could start by being challenged to identify an error in the implementation of the gravity equations in sample code given to them. Next, students modify the code to correctly reflect the mass of the Earth and a small artificial communications satellite orbiting around it. They can vary different parameters in the code such as the distance from Earth or initial speed and see how those parameters affect the path of the satellite (*HS-ESS1-4*). At what initial launch speeds will the satellite stay in orbit? What is the tradeoff between the cost of fuel and the payload mass?

Appendix 3 in this *CA Science Framework* provides guidance about teaching computer coding aligned with the CA NGSS.

While Kepler's laws present a simple view of orbital shapes and periods, the *NRC Framework* pushes teachers to emphasize the importance of **changes [CCC-7]** in orbits, as these changes have large impacts on Earth's internal systems:

> *Orbits may change due to the gravitational effects from, or collisions with, other objects in the solar system. Cyclical changes in the shape of Earth's orbit around*

> *the sun, together with changes in the orientation of the planet's axis of rotation, both occurring over tens to hundreds of thousands of years, have altered the intensity and distribution of sunlight falling on Earth. These phenomena cause cycles of ice ages and other gradual climate changes.* (National Research Council 2012, 176)

Using realistic computer simulations of Earth's orbit (*HS-ESS1-4*), students can **investigate [SEP-3]** the **effects [CCC-2]** collisions (such as the impact that led to the creation of the Moon) or explore the variation in the Earth-Sun distance to look for **evidence [SEP-7]** of cyclic **patterns [CCC-1]***.* They would discover some cyclic **patterns [CCC-1]** called Milankovitch cycles, which have strong influence on Earth's ice age **cycles [CCC-5]***.*

Applications of Electromagnetic Forces

Up to this point, this IS has focused on interactions *between* different objects via electrostatic, electromagnetic, and gravitational forces. Now, students look at how forces work *within* materials at the microscopic level in order to explain macroscopic properties. In the middle grades, students developed conceptual models of atoms and molecules making up the **structure [CCC-6]** of solids, liquids, and gases. Here they **develop and refine those models [SEP-2]**, and understand that the **stability [CCC-7]** and properties of solids depend on the electromagnetic forces between atoms, and thus on the **types and patterns [CCC-1]** of atoms and molecules within the material.

Most collegiate STEM education is highly departmentalized, with students majoring in biology, chemistry, geology, astronomy, physics, engineering, mathematics, or related fields. Students may inadvertently assume that particular topics belong to one domain or another and may fail to see the elegance and power of crosscutting concepts that have applications in a variety of fields. Teachers and students of physics may therefore have difficulty understanding the relevance of *HS-PS2-6* which focuses on how the "molecular-level structure is important in the functioning of designed materials."

This PE sounds like it belongs in a chemistry course because it deals with “molecular-level structure” or perhaps in engineering because it deals with the “functioning of designed materials.” In reality, this performance expectation, like many, can be equally valuable in many different disciplines of science and engineering. An emphasis on material strength allows this content to flow well from the previous material in this course.

Students can begin by **investigating [SEP-3]** materials with macroscopic structure such as rope, yarn, knitted fabrics, individual clay bricks, clumps of soil, wood, or handmade paper. Students can sort the objects based on common **patterns [CCC-1]** in their structures. Rope, yarn, and wood all have fibers that run dominantly in one direction while knitted fabrics and paper both have fibers going in multiple directions. Clay bricks and clumps of soil have tiny particles in a three-dimensional matrix. All materials also have structure at the atomic level. These structures are held together by attractions caused by electromagnetic forces that can be different strengths (just as a clump of soil is weaker than a brick that has a similar internal structure because the attractions holding the soil particles together are weak). Hence, different materials have different properties that are determined by features at the molecular level.

To develop a model of molecular level structure, students must first refine their model of the substructure of an atom. The mass of the atom is determined by its nucleus, but its electronic structure extends far outside the region where the nucleus sits. An important idea here is that the geometric size of more massive atoms is not very different from that of a hydrogen atom. An explanation for this is the fact that the higher charge of the nucleus pulls the electrons more strongly, so though there are more electrons, and their **patterns [CCC-1]** are more complex, there is a roughly common size **scale [CCC-3]** for all atoms. Models for materials help make the importance of this fact visible, as students see that you can fit many different combinations of atoms together in space and, thus, make a great variety of molecules and materials. For HS-PS2-6, students need only a qualitative, not quantitative understanding.

HS-PS2-6 requires students to **obtain, evaluate, and communicate information [SEP-8]** related to the properties of various materials and their consequent usefulness in particular applications. The role of engineering in this activity is not to make a design, but to use engineering thinking to **explain [SEP-6]** how the substructure relates to the macroscopic properties of the material and then **communicate [SEP-8]** that understanding. HS-PS2-6 emphasizes the skills in Appendix M (Connections to the Common Core State Standards for Literacy in Science and Technical Subjects) of the NGSS:

> *Reading in science requires an appreciation of the norms and conventions of the discipline of science, including understanding the nature of evidence used, an attention to precision and detail, and the capacity to make and assess intricate arguments, synthesize complex information, and follow detailed procedures and accounts of events and concepts. [Students] need to be able to gain knowledge from elaborate diagrams and data that convey information and illustrate scientific concepts. Likewise, writing and presenting information orally are key means for students to assert and defend claims in science, demonstrate what they know about a concept, and convey what they have experienced, imagined, thought, and learned.* (NGSS Lead States 2013b)

Students may **obtain information [SEP-8]** about the molecular-level interactions of various electrical conductors, semiconductors, and insulators to explain why their unique properties make them indispensable in the design of integrated circuits or urban power grids. For example, if students understand that the fundamental structure of metals, such as copper, aluminum, silver, and gold, can be described as a myriad of nuclei immersed in a “sea of mobile electrons,” they can then explain that these materials make good conductors because the electrons are free to migrate between nuclei under applied electromagnetic forces. By contrast, when students investigate the molecular level properties of covalent compounds, such as plastics and ceramics, they should note that these compounds behave as electrical insulators because their electrons are locked in bonds and therefore resistant to the movement that is necessary for electric currents. As students learn to communicate such information, they obtain a better appreciation of **cause and effect [CCC-2]*.*** For example, students should be able to explain that electromagnetic interactions at the molecular level (causes) result in properties (**effects [CCC-2]**) at the macro-level and that these properties make certain materials good candidates for specific technical applications.

Physics in the Universe - Instructional Segment 3: Energy Conversion and Renewable Energy

We use **energy [CCC-5]** every moment of every day, but where does it all come from? Our body utilizes energy stored in the chemical potential energy of bonds between the atoms of our food, which were rearranged within plants using energy from the Sun. The light energy shining out from our computer was converted from the electric potential energy of electrons from the wall socket that flowed through wires that may trace back to a wind turbine, which did work harnessing the movement of air masses, which absorbed thermal energy from the solid Earth, which originally absorbed the energy from the Sun. Each of these examples represents the **flow of energy [CCC-5]** within different components of the Earth **system [CCC-4]**. With each interaction, energy can change from one form to another. These ideas comprise perhaps the most unifying crosscutting concept in physics and all other science, **conservation of energy [CCC-5]**.

Physics in the Universe – Instructional Segment 3:
Energy Conversion and Renewable Energy

Guiding Questions

- How do power plants generate electricity?
- What engineering designs can help increase the efficiency of our electricity production and reduce the negative impacts of using fossil fuels?

Performance Expectations

Students who demonstrate understanding can:

HS-PS2-5 Plan and conduct an investigation to provide evidence that an electric current can produce a magnetic field and that a changing magnetic field can produce an electric current. [Assessment Boundary: Assessment is limited to designing and conducting investigations with provided materials and tools.]

HS-PS3-1. Create a computational model to calculate the change in the energy of one component in a system when the change in energy of the other component(s) and energy flows in and out of the system are known. **[Clarification Statement: Emphasis is on explaining the meaning of mathematical expressions used in the model.] [Assessment Boundary: Assessment is limited to basic algebraic expressions or computations; to systems of two or three components; and to thermal energy, kinetic energy, and/or the energies in gravitational, magnetic, or electric fields.]**

HS-PS3-2 Develop and use models to illustrate that energy at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects). **[Clarification Statement: Examples of phenomena at the macroscopic scale could include the conversion of kinetic energy to thermal energy, the energy stored due to position of an object above the earth, and the energy stored between two electrically-charged plates. Examples of models could include diagrams, drawings, descriptions, and computer simulations.]**

HS-PS3-5 Develop and use a model of two objects interacting through electric or magnetic fields to illustrate the forces between objects and the changes in energy of the objects due to the interaction. **[Clarification Statement: Examples of models could include drawings, diagrams, and texts, such as drawings of what happens when two charges of opposite polarity are near each other.] [Assessment Boundary: Assessment is limited to systems containing two objects.]**

HS-PS3-3. Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.* **[Clarification Statement: Emphasis is on both qualitative and quantitative evaluations of devices. Examples of devices could include Rube Goldberg devices, wind turbines, solar cells, solar ovens, and generators. Examples of constraints could include use of renewable energy forms and efficiency.] [Assessment Boundary: Assessment for quantitative evaluations is limited to total output for a given input. Assessment is limited to devices constructed with materials provided to students.]**

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-ESS3-2. Evaluate competing design solutions for developing, managing, and utilizing energy and mineral resources based on cost-benefit ratios.* **[Clarification Statement: Emphasis is on the conservation, recycling, and reuse of resources (such as minerals and metals) where possible, and on minimizing impacts where it is not. Examples include developing best practices for agricultural soil use, mining (for coal, tar sands, and oil shales), and pumping (for petroleum and natural gas). Science knowledge indicates what can happen in natural systems—not what should happen.]**

HS-ESS3-3. Create a computational simulation to illustrate the relationships among management of natural resources, the sustainability of human populations, and biodiversity. **[Clarification Statement: Examples of factors that affect the management of natural resources include costs of resource extraction and waste management, per-capita consumption, and the development of new technologies. Examples of factors that affect human sustainability include agricultural efficiency, levels of conservation, and urban planning.] [Assessment Boundary: Assessment for computational simulations is limited to using provided multi-parameter programs or constructing simplified spreadsheet calculations.]**

HS-ETS1-1. Analyze a major global challenge to specify qualitative and quantitative criteria and constraints for solutions that account for societal needs and wants.

HS-ETS1-2. Design a solution to a complex real-world problem by breaking it down into smaller, more manageable problems that can be solved through engineering.

HS-ETS1-3. Evaluate a solution to a complex real-world problem based on prioritized criteria and trade-offs that account for a range of constraints, including cost, safety, reliability, and aesthetics as well as possible social, cultural, and environmental impacts.

HS-ETS1-4. Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem.

*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	**Highlighted**	**Highlighted**

Science and Engineering Practices	Disciplinary Core Ideas	Crosscutting Concepts
[SEP-1] Asking Questions and Defining Problems **[SEP-2] Developing and Using Models** **[SEP-3] Planning and Carrying Out Investigations** **[SEP-4] Analyzing and Interpreting Data** **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)**	**PS3.D: Energy in Chemical Processes and Everyday Life** **PS3.A: Definitions of Energy** **PS3.B: Conservation of Energy and Energy Transfer** **PS3.C: Relationship Between Energy and Forces**	**[CCC-2] Cause and Effect** **[CCC-3] Scale, Proportion, and Quantity** **[CCC-4] System and System Models** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation**

[SEP-7] Engaging in Argument from Evidence **[SEP-8] Obtaining, Evaluating, and Communicating Information**		
Highlighted California Environmental Principles & Concepts: Principle I The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services. Principle II The long-term functioning and health of terrestrial, freshwater, coastal and marine ecosystems are influenced by their relationships with human societies. Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter. Principle IV The exchange of matter between natural systems and human societies affects the long term functioning of both. Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes.		
CA CCSS Math Connections: N-Q.1-3; MP.2; MP.4		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: SL.11-12.5; RST.11-12.1,8, WHST.9-12.2.a-e, 7,8,9		

The first law of thermodynamics elaborates on the **conservation of energy [CCC-5]** by saying that the total energy of an isolated system is constant, and that although energy can be transformed from one form to another, it cannot be created nor destroyed. Conservation of energy requires that changes in energy within a system must be balanced by energy flows into or out of the system by radiation, mass movement, external forces, or heat flow. The vignette for the four-course physics provides a framework for discussing many of these energy forms and how they convert from one to another. This IS selects a subset of processes that follow a storyline of tracing the energy flow of our electricity back to various power plants and renewable energy sources. This approach provides integration with timely issues in engineering and Earth science.

Electricity in Daily Life

Before students jump into the physical processes that allow us to generate electricity, students should be able to compare the range of different electricity generation methods currently utilized. This basic familiarity will make all the physical principles more tangible, but it also allows students to engage in a real-world decision making process (CA *EP&C V*) because each of these **energy [CCC-5]** sources has advantages and disadvantages (*ESS3.A*). More than half of the electricity in California was generated from fossil fuels in 2013 (California Energy Commission Energy Almanac 2016). Many fossil fuel power plants emit toxic pollutants and can impact the health of ecosystems and people nearby (CA *EP&C IV*). Students can **analyze data [SEP-4]** from maps of the amount of pollution in their community (see the California Office of Environmental Health Hazard Assessment, Cal Enviroscreen 2.0 at http://oehha.ca.gov/ej/ces2.html) and **ask questions [SEP-1]** about the pollution source and how it affects human health. Fossil fuels also emit greenhouse gases that do not have a direct impact on health but contribute to global climate change (*ESS2.D; CA EP&C III; HS Chemistry course IS4*). At the same time, these fuel sources are cheap and plentiful. New technology in the last few years has made other energy sources increasingly viable and California has pledged to increase the use of these renewable energy sources to one third of California's electricity supply by 2020 (up from less than 20 percent a decade earlier). What issues have been driving California's decisions? Excellent classroom resources exist for teaching about different electricity generation strategies, including formats where students debate the relative costs and benefits of each energy source (*HS-ESS3-2*) (see http://www.switchenergyproject.com/education/CurriculaPDFs/SwitchCurricula-Secondary-Introduction/SwitchCurricula-Secondary-GreatEnergyDebate.pdf).

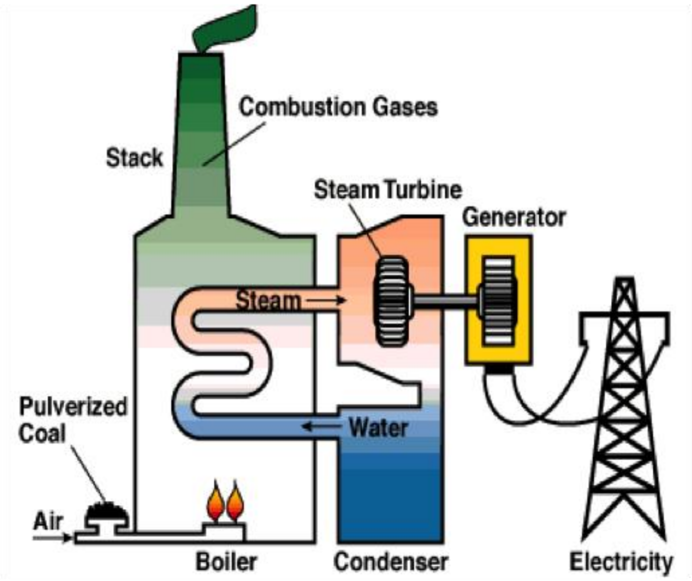
The Physics of Power Plants

A power plant can be thought of a **system [CCC-4]**, and **energy [CCC-5]** is constantly **flowing [CCC-5]** out of the system in the form of electricity. The energy in all systems is finite, so a power plant would quickly run out of energy if it did not have a constant source of fuel. Each power plant is built to produce a certain amount of energy in a given time (i.e., "power"). Students can use internet resources to find the power generation capacity and fuel source of the power plant closest to their school. They can then create a **mathematical model [SEP-2]** *(HS-PS3-1)* to calculate the amount of fuel required to operate the power plant in a day or a year, knowing that the electrical **energy flowing out of the system [CCC-5]** has to equal the energy from the fuel sources entering into the system (at this point, students can neglect efficiency – it will be introduced later).

At the middle grade level, students explored various forms of energy [CCC-5], determining the factors that affect kinetic energy (MS-PS3-1) and potential energies (MS-PS3-2), the relationship between kinetic energy and thermal energy (MS-PS3-4), and the concept of energy transfer in engineering design (MS-PS3-3) and constructing scientific explanations (MS-PS3-5). Clarification statements for several of these PEs explicitly state that calculations are excluded from the middle grade level. In high school, students are now ready to quantify the amount of energy objects have and transfer during interactions. The high school Chemistry in the Earth System course also pays explicit attention to these topics and emphasizes thermal and chemical potential energies.

The middle grade PEs are written broadly such that different students might come into high school with knowledge of different forms of **energy [CCC-5]**. Here, students should organize what they know about these different forms of energy to make the distinction between energy from particle motion, potential energy due to interactions between particles, and radiation. Potential energies arise from forces that act at a distance like gravity and electromagnetism (as discussed in IS2). Students "**develop and use a model [SEP-2]** that **energy [CCC-5]** at the macroscopic scale can be accounted for as a combination of energy associated with the motions of particles (objects) and energy associated with the relative position of particles (objects)" (*HS-PS3-2*). In other words, the sum of the kinetic and potential energy of component particles (energy of motion and position) must total the bulk energy measured at the macroscopic level. Using diagrams, drawings, descriptions, and/or computer simulations, students should be able to illustrate this summative relationship. This PE is designed to help students bridge concepts traditionally associated with chemistry (e.g. the energy of atoms and molecules) with the concepts traditionally associated with physics (e.g. the energy of macroscopic objects). Students can develop this model by making a poster of the different stages in a typical thermoelectric power plant (figure 7.51). To generate electricity, these power plants use heat energy to eventually produce electricity (most fossil fuel, nuclear, geothermal, and even concentrated solar power plants fit in this category). They usually heat water into steam, which changes the relative position of the particles from being densely packed in a liquid into particles that are much farther apart. This change in relative position requires an increase in the electrostatic potential energy of the water molecules, which we see macroscopically as having 'absorbed' the latent heat of vaporization. The power plants then converts thermal energy into kinetic energy. Individual molecules (usually water molecules heated to steam) are moving very fast and collide with a turbine, transferring some of the kinetic energy in randomly moving molecules (i.e., thermal energy) into the systematic motion of the turbine (i.e., kinetic energy of the object). The turbine will turn the crank of a generator to convert the kinetic energy into electricity, but it will not be 100 percent efficient because molecular collisions will result in energy being transferred to particles moving in random directions again, detracting from the total energy available in the object to move the crank forward. At the macroscopic level, we attribute this lower efficiency to the process we call friction. At each stage, students **communicate [SEP-8]** the forms of **energy [CCC-5]** at both the microscopic and macroscopic level.

Figure 7.51. Schematic of a Power Plant



Source: Center for Climate and Energy Solutions 2015.

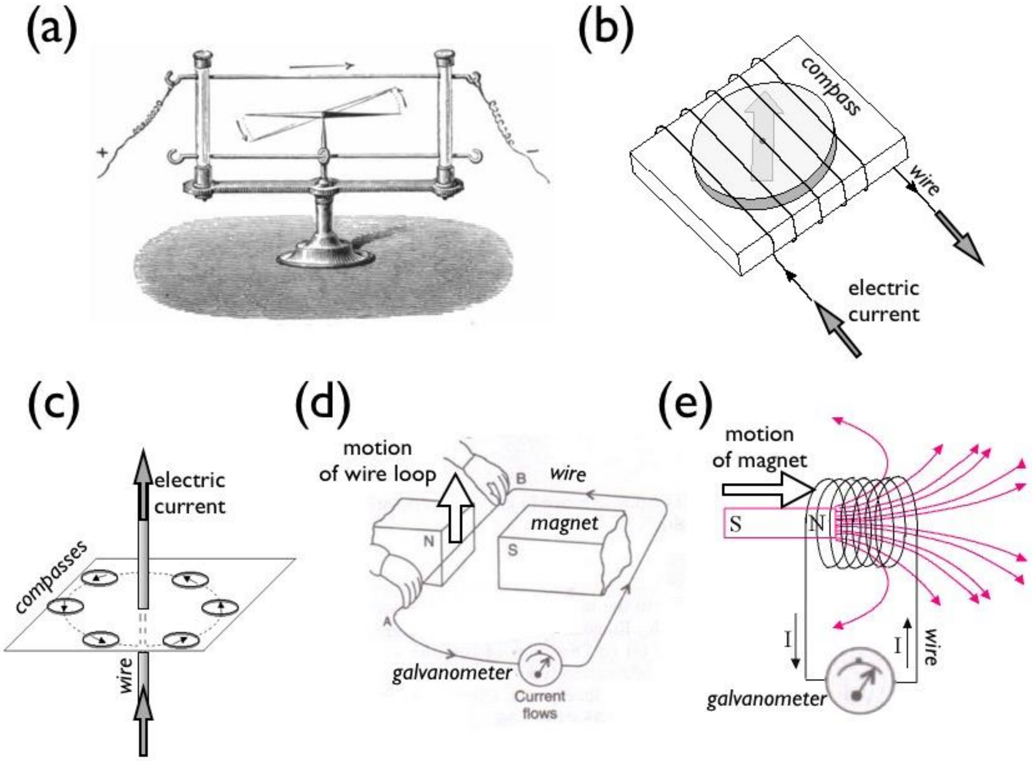
Converting Kinetic Energy to Electricity

Electric generators are an essential component in nearly all types of electric power generation, including coal, nuclear, natural gas, geothermal, tidal, wind turbines, hydroelectric (basically everything except fuel cells and solar photovoltaic). Students might try to apply their understanding of microscopic collisions to the **energy [CCC-5]** conversion processes within a generator to come to the incorrect conclusion that these collisions impart kinetic energy to electrons, which move through a circuit. In order to overcome this misconception, students must replace that notion with a correct model for energy conversion between kinetic energy of objects and electricity. This model requires that students continue their exploration of electric and magnetic forces from IS2.

For many years, scientists considered electric and magnetic forces to be independent of each other, but in 1819, Hans Christian Ørsted discovered that electric current generates a magnetic force, and in 1839, Michael Faraday showed that magnetism could be used to generate electricity. Finally, in 1860, James Clerk Maxwell derived equations to show how electricity and magnetism are related. Students will follow in their footsteps to **plan and carry out investigations [SEP-3]** that illustrate the relationship between electricity and magnetism (HS-PS2-5). These interactions are essential for understanding how most electricity is generated in power plants.

Students might recreate Ørsted's simple **investigation [SEP-3]** in which he noticed that a compass needle would be deflected from magnetic north when an electric current passed through a wire that was held above the magnet (figure 7.52a). They can be given the challenge of getting the compass needle to deflect a fixed amount (e.g., so that it points northeast at 45° instead of north). They will need to explore what happens when they change the direction of the wire, the voltage through the wire, or the number of winds of the wire around the compass (figure 7.52b) or move the compass to different locations around the wire (figure 7.52c). Students should then be able to create an informative poster **communicating [SEP-8]** how each of these variables **affects [CCC-2]** the compass needle.

Figure 7.52. Magnetic Fields and Electric Currents



(a and b): Ørsted’s experiment illustrates that an electric current generates a magnetic field. (c): Sensitive compasses can detect the magnetic field surrounding a current-carrying wire. (d): Moving a looped wire through a magnetic field generates a current within the wire. (e): Moving a magnet through a looped wire generates an electric current. Source: Privat-Deschanel 1876; Barclay n.d.; Narula n.d.; Singh 2016; Pellissippi State Community College Natural and Behavioral Sciences Department n.d.

Students can also place iron filings on a glass plate that lies on top of their wire coil and use that to map out the strength and orientation of the magnetic field. As they tap on the plate, the filings align with the magnetic field, with greater concentrations moving to those locations where the field is strongest. Adding a permanent magnet, students can use the iron filings to visualize the interaction between the magnetic fields of the wire and the permanent magnet. Equipped with data on the direction and relative magnitude of the field, students can draw a qualitative **model [SEP-2]** of the magnetic field using vectors at various locations surrounding the wire (*HS-PS3-5*). In such a model, the direction of the arrows indicates the direction of the field, while the length of these arrows indicates its magnitude.

After gathering evidence that an electric current creates a magnetic field, students should investigate if the reverse is also true. They **plan and carry out an investigation [SEP-3]** to see if a changing magnetic field can induce an electric current. The simplest investigation requires connecting a galvanometer in a loop and moving the far side of the loop back and forth between two strong magnets (figure 7.52d). Students will observe the galvanometer needle deflect in opposite directions depending on which way the wire is moved (indicating that the electric current flows in different directions as the wire moves different directions). Students can use this equipment to explore other variables. For example, they may coil the wire and move the magnet through the center of the coil and see a similar response (figure 7.52e). This principle is important for creating electric generators. While students may not be able to make that leap themselves, they should be able to **construct an explanation [SEP-6]** about how this principle could be used to make a generator in which there is a constant flow of electricity. Their explanation could rely on diagrams (pictorial **models [SEP-2]**).

Converting Light to Electricity

Solar panels convert light **energy [CCC-5]** into electricity. Students will learn more about the nature of light in IS5, but the focus in this IS is on understanding the qualitative interactions between light energy and the matter in solar cells well enough to communicate it to others (*HS-PS4-5*). Atoms in a solar cell absorb the light energy, which causes electrons to be knocked loose. Free electrons are a key ingredient to an electric current, but currents require those electrons to move systematically around a circuit. Silicon semiconductors are set up so that they have a systematic bias where electrons preferentially move in a single direction. How does this happen? Pure silicon forms systematic crystal structures, but adding small amounts of some types of elements disrupts those shapes and can even allow each silicon atoms to be in a configuration where it can accept an additional electron. Adding other specific elements causes the silicon atoms in the lattice to end up with an extra electron. Engineers make thin crystals of each type (one with contaminants that have extra electrons and one with 'holes' for additional electrons) and stack them on top of one another. Now, when light hits the atoms in this material, the free electrons are repelled by the extra electrons in one layer and automatically move towards the layer with space for additional electrons. As the Sun continues to shine and more electrons get knocked loose, they always flow in the same direction and set up a steady electric current. Students must be able to understand this interaction between light and matter well enough to **communicate [SEP-8]** it to others (*HS-PS4-5*). Groups of students could make a fact sheet, a stop-motion animation, or skit to articulate the ideas.

Physics of the Universe Snapshot 7.13: Evaluating Plans for Renewable Power Plants

Investigative phenomenon: Windmills and hydroelectric power plants convert energy from the movement of air and water into electricity.

The city where Mrs. G's city is located wants to switch to 100 percent clean and renewable energy. They are considering two options, a series of small hydroelectric power dams on a river coming out of the mountains and a set of windmills in the flat sections of town where it is always windy. Mrs. G divides the class into small groups and she assigns each one to either create a proposal for wind energy or a plan for hydroelectric power. Teams begin by using **mathematical thinking [SEP-5]** to calculate the amount of energy their proposed project would generate. The hydroelectric group assumes that the dams will harness gravitational potential energy and use the appropriate equations to evaluate the energy produced by different height dams (Energy = mass x g x height, where the water mass is determined by the average annual flow rate on the river calculated using data collected by a USGS stream gauge that is available on the internet). The wind energy group assumes that the kinetic energy of the air is harnessed and uses the appropriate equations to evaluate the energy produced by different sized windmills (Energy = ½ x mass x velocity^2, where the mass is calculated using the average density of air combined with the size of the blades and the speed of the wind. Wind velocity is calculated using the average values from a nearby weather station that posts hourly data on the internet).

Investigative phenomenon: Electric generators are not 100% efficient.

Mrs. G teaches the students about the concept of efficiency when it comes to electric power generation where only a fixed **proportion [CCC-3]** of the energy is actually successfully converted to electricity (while a large fraction is wasted as heat).

Investigative problem: Which clean energy power source will best meet the needs of our community?

Each team **obtains information [SEP-8]** about the efficiency of their energy generation technology and uses it update their estimate of the electrical energy they can generate. With these basic calculations, each team must develop a specific proposal for a power plant that will provide 100 percent of the city's energy. The wind teams must decide how many windmills, and the diameter of the blades. The hydroelectric teams must decide how many dams and their heights. Each team produces a report outlining the benefits of their plan. The class then hosts a town hall meeting where teams **communicate [SEP-8]** their plans and present an argument that their proposal is better than the competing plans. This **argument should be supported by evidence [SEP-7]** that goes beyond the simple energy calculations but also takes into account the relative benefits and impacts of each technology on natural systems (CA EP&C II; for example, dams destroy aquatic habitat, use large volumes of CO_2 in their cement, and result in water lost to evaporation; wind turbines obstruct scenic views, occupy large amounts of land, and only provide intermittent energy). These competing factors enter into all real world decisions about energy generation (CA EP&C V). Students can use a spreadsheet program to try to quantify some of these effects as they compare the impact of each proposal on the local ecosystem (HS-ESS3-3).

Engineering Connection: Engineering Energy Conversion Devices

Now that students have learned extensively about the theory behind **energy conversion [CCC-5]** devices, they are now tasked with an engineering challenge to create one themselves (*HS-PS3-3*). The vignette in High School Four Course Model – Physics section of this *CA Science Framework* includes a template of what this design challenge might look like. The first stage of the engineering design process is to place the goal in the context of the major global challenge of providing affordable electrical energy without the problems associated with fossil fuels (*HS-ETS1-1*). Students evaluated the impacts of different electricity sources at beginning of this IS, including a discussion of how fossil fuels contribute to global climate change. The High School Three-course Model – Chemistry in the Earth System course emphasizes physical mechanisms causing climate change and the High School Three Course Model – The Living Earth course explores its effects on the biosphere. Depending on the sequence of courses within each school district, this IS should draw strong connections to those courses. Designing, building, and improving energy conversion devices that are more efficient or that pollute less involves breaking down the complex global problem into more manageable problems that can be solved through engineering (*HS-ETS1-2*). Students have learned some of the scientific principles behind the engineering tools that can help address the challenge throughout this IS. Students now choose to build their own wind turbines, hydroelectric power plants, solar panels, or other mini version of a power plant that transforms energy from less useful forms, such as wind, sunlight, or motion, into electricity (arguably the most convenient and useful form of energy in our modern world). Students learn to work within engineering constraints as they strive to maximize efficiency (generate the largest power output possible) while taking into account prioritized criteria and trade-offs (*HS-ETS1-3*). Students can measure outputs and then refine their designs to maximize efficiency given constant inputs. Students can also utilize existing computer simulations to investigate the impact of these different energy solutions (*HS-ETS1-4*).

Physics in the Universe – Instructional Segment 4: Nuclear Processes and Earth History

Energy [CCC-5] related to changes in the nuclei of atoms drives about 20 percent of California's electricity generation (California Energy Commission Energy Almanac 2016) (from fission in nuclear power plants), half the heat flowing upwards from Earth's interior (from the radioactive decay of unstable elements) (Gando et al. 2011), and all of the energy we receive from the Sun (from nuclear fusion in its core). In this IS, students will develop **models [SEP-2]** for these processes.

Physics in the Universe – Instructional Segment 4: Nuclear Processes and Earth History
Guiding Questions - *What does $E=mc^2$ mean?* - *How do nuclear reactions illustrate conservation of energy and mass?* - *How do we determine the age of rocks and other geologic features?*
Performance Expectations
Students who demonstrate understanding can: HS-PS1-8 Develop models to illustrate the changes in the composition of the nucleus of the atom and the energy released during the processes of fission, fusion, and radioactive decay. **[Clarification Statement: Emphasis is on simple qualitative models, such as pictures or diagrams, and on the scale of energy released in nuclear processes relative to other kinds of transformations.] [Assessment Boundary: Assessment does not include quantitative calculation of energy released. Assessment is limited to alpha, beta, and gamma radioactive decays.]** HS-ESS1-5. Evaluate evidence of the past and current movements of continental and oceanic crust and the theory of plate tectonics to explain the ages of crustal

rocks. **[Clarification Statement: Emphasis is on the ability of plate tectonics to explain the ages of crustal rocks. Examples include evidence of the ages oceanic crust increasing with distance from mid-ocean ridges (a result of plate spreading) and the ages of North American continental crust increasing with distance away from a central ancient core (a result of past plate interactions).] (Also addressed in the High School Chemistry in the Earth System course)**

HS-ESS1-6. Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. **[Clarification Statement: Emphasis is on using available evidence within the solar system to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, moon rocks, and Earth's oldest minerals), the sizes and compositions of solar system objects, and the impact cratering record of planetary surfaces.] (Also addressed in the High School Living Earth course)**

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.] (Also addressed in the High School Living Earth course)**

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	**PS1.C: Nuclear Processes**	[CCC-1] Patterns
[SEP-2] Developing and Using Models	**PS1.A Structure and Properties of Matter**	[CCC-2] Cause and Effect
[SEP-4] Analyzing and Interpreting Data	**ESS1.C: The History of Planet Earth**	[CCC-3] Scale, Proportion, and Quantity
[SEP-5] Using mathematics and Computational Thinking	**ESS2.B: Plate Tectonics and Large-Scale System Interactions**	[CCC-4] System and System Models
[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)		[CCC-5] Energy and Matter: Flows, Cycles, and Conservation
[SEP-7] Engaging in		[CCC-6] Structure and Function
		[CCC-7] Stability and Change

Argument from Evidence **[SEP-8] Obtaining, Evaluating, and Communicating Information**		
Highlighted California Environmental Principles & Concepts: Principle I The continuation and health of individual human lives and of human communities and societies depend on the health of the natural systems that provide essential goods and ecosystem services. Principle II The long-term functioning and health of terrestrial, freshwater, coastal and marine ecosystems are influenced by their relationships with human societies. Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter. Principle IV The exchange of matter between natural systems and human societies affects the long term functioning of both. Principle V Decisions affecting resources and natural systems are based on a wide range of considerations and decision-making processes.		
CA CCSS Math Connections: MP.2; MP.4		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: SL.11-12.4; RST.11-12.1,8, WHST.9-12.2.a-e, 7,9		

Students will need to apply an understanding of the internal **structure [CCC-6]** of atoms and be able to read the periodic table, topics introduced in the High School Chemistry in the Earth System course and no longer addressed at the middle grade level. If students have not yet taken High School Chemistry in the Earth System, teachers can use nuclear processes to introduce these topics.

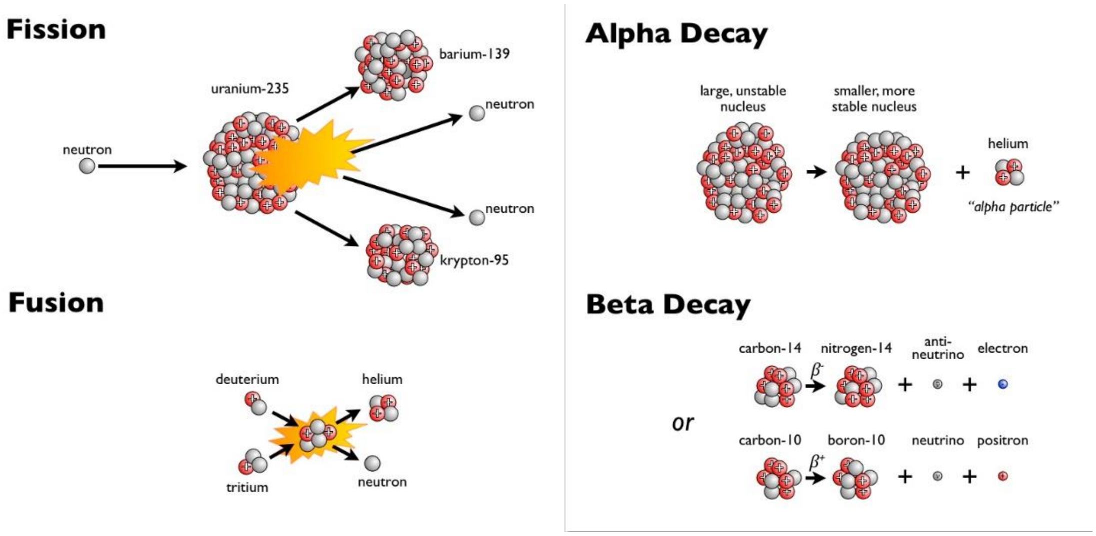
Changes in the nucleus occur at a length **scale [CCC-3]** too small to observe directly, but students can detect **evidence [SEP-7]** of these processes by looking at energy and matter that radiate out of the nucleus as a result of these changes. One can think of these emissions as an **effect [CCC-2]** and **develop a model [SEP-2]** that **explains [SEP-6]** the **cause [CCC-2]**. Students begin the IS by making observations of a cloud chamber (see MIT Video, Cloud Chamber at http://video.mit.edu/watch/cloud-chamber-4058/) (as a video clip or classroom demonstration). Strange streaks whiz through the cloud chamber. Students can measure background radiation using a Geiger counter or even a smartphone app (see Australian Nuclear Science and Technology Organization, Smart phone radiation detector 'app' tests positive at http://www.ansto.gov.au/AboutANSTO/MediaCentre/News/ACS049898). With these observations, students now **obtain information [SEP-8]** about the discovery of radioactivity and how scientists in the late 1800's like Becquerel and the Curies determined that the particles emitted during radioactivity had mass, were often charged, and emanated in high concentrations from different types of natural materials. Over time, this understanding has led to the modern **models [SEP-2]** of radioactivity and the modern tools for measuring its effects. These concepts can generally not be explored in direct experimentation in the classroom, so students will need to **analyze data [SEP-4]** from external sources and simulations to develop their own understanding of these models.

Scientists know of only four fundamental interactions, also known as fundamental forces: gravitational, electromagnetic, strong nuclear and weak nuclear. All interactions between matter in the Universe involve one of these forces. Students studied the first two during IS2, and the focus in this IS is on the effects of the remaining two. The strong force ensures the **stability [CCC-7]** of ordinary matter by binding the atomic nucleus together, while the weak mediates radioactive decay. Although the strong and weak nuclear forces are essential for matter, as we know it, to exist, they are difficult to conceptualize and relate to because they operate at **distances scales [CCC-3]** too small to be seen. As the nucleus gets larger, forces holding nuclei together are overcome by electrostatic repulsion, which is why the largest atoms on the periodic table are unstable. It is this instability that result in the nucleus changing in one or more ways.

The Earth receives more **energy [CCC-5]** from the Sun in an hour and a half than all of humanity uses in a year, but this energy does not come from nothing. Nuclear reactions, too, must obey **conservation [CCC-5] laws**, but now students must apply the principle of mass-energy equivalence ($E=mc^2$) to revise the view that matter is conserved as atoms, to a more accurate view that the number of nucleons (sum of protons and neutrons) is conserved. Neither mass, nor the number of atoms of each type are conserved in nuclear processes, and although such mass conservation "laws" are applicable to gravitational and electromagnetic processes they must be revised and refined as we examine nuclear processes. This revision and refinement process should be stressed as an essential part of the nature of science.

Nuclear **changes [CCC-7]** all release large amounts of **energy [CCC-5]**, but they do so by different mechanisms. Scientists have recognized several classes of nuclear processes, including combining small nuclei to make larger ones (fusion) and larger nuclei emitting smaller pieces (fission, alpha decay, and beta decay). Students **develop models [SEP-2]** to illustrate the **changes [CCC-7]** in the composition of the nucleus of the atom and the **energy [CCC-5]** released during each of these processes (*HS-PS1-8*). Such models could be in the form of equations or diagrams (figure 7.53). Although it is not necessary to include quantitative calculations, the models should communicate the conservation of the combined mass-energy system.

Figure 7.53. Models of Nuclear Processes in Atoms



Sources: Adapted from Stefan-XP 2009; Pbech 2008; Thomas Jefferson National Accelerator Facility – Office of Science Education 2015a, 2015b.

In fusion, small nuclei combine together to form larger ones. Since all nuclei have positive charges (made only of positive protons and neutral neutrons), electrostatic forces will tend to repel nuclei apart from one another. The closer nuclei get to one another, the stronger the electrostatic repulsion. Nuclei can get very close to one another if they collide when they are moving very fast. If they manage to get close enough to one another, another interaction becomes important: the strong nuclear force which is what holds nuclei together in the first place. Like creating a new chemical bond, creating new strong force interactions releases **energy [CCC-5]**. Students will revisit fusion and apply their qualitative model of it to stars in IS6, since stellar cores are the only place where fusion naturally occurs. Efforts have been made to use fusion to make energy on Earth, but the engineering task is challenging. If scientists and engineers can get it to work, fusion would be cleaner and safer than just about any other known energy source and is therefore a worthwhile area of research. Even though fusion can be recreated in laboratories, a large amount of energy needs to be utilized to speed nuclei up fast enough to achieve fusion. Unless the fusion device is extremely efficient, it ends up taking more energy to start the fusion than the fusion actually releases. California hosts the most advanced fusion experiment in the world at the Lawrence Livermore National Laboratory where scientists and engineers are working daily to make breakthroughs. Students could explore an interactive computer simulation of the experiment where they adjust the speed at which atoms are accelerated until fusion is achieved, making measurements about the amount of energy used in the device and the amount of energy released by fusion.

Weak interaction processes (beta decay) should be introduced as **changes [CCC-7]** in which neutrons transform into protons or protons transform to neutrons. Beta decay allows atoms to move closer to the optimal ratio of protons and neutrons, and is key to understanding why all stable nuclei have roughly equal numbers of protons and neutrons, with a few more neutrons as nuclei gets bigger. Protons have an electric charge while neutrons are neutral and have a slightly larger mass. Conservation laws dictate that the charge and extra mass cannot just appear or disappear but must come from somewhere. Applying the reasoning from conservation laws, students recognize that other subatomic particles like positrons and neutrinos must exist along with protons, neutrons, and electrons.

Sometimes the competition between different forces within the nucleus cause it to spontaneously split apart to form two or more smaller nuclei. One of these smaller products is often a helium nucleus composed of two protons and two neutrons. This particle is often called an alpha particle, so this type of fission is referred to as alpha decay. The smaller nuclei require less total binding energy, so some of that energy is converted into kinetic energy causing the smaller nuclei to rapidly fly away from one another. These nuclei are also usually unstable because smaller nuclei require a different ratio of protons to neutrons in order to be stable than the original larger nucleus. These smaller nuclei will often release even more energy either undergoing beta decay or by releasing energy by gamma radiation when their component protons and neutrons rearrange to a lower (more stable) energy configuration.

Nuclear power plants rely on the release of **energy [CCC-5]** from nuclear **changes [CCC-7]** in uranium (and sometimes plutonium). Nuclei of these atoms are unstable and naturally decay primarily by alpha, beta, and gamma decay, but this process is very slow. Reactors extract most of their energy by inducing fission. This is accomplished primarily by separating out uranium-235 (a nucleus with 92 protons and 143 neutrons) from other forms of uranium with different numbers of neutrons. These other forms of uranium absorb neutrons, which prevents the fission process from speeding up. When fission occurs in one atom of this purer uranium, neutrons that are given off are likely to collide with other uranium atoms and induce them to fission. As a result, energy release can be maintained at a rate far above the typical background level for naturally occurring concentrations of uranium. This energy is used to heat water just like other thermoelectric power plants. Students can use an online simulator to model the fission process and can be given the challenge to adjust the simulator settings to find the minimum concentration of uranium-235 required to maintain a certain energy output from fission (see PhET, Nuclear Fission at https://phet.colorado.edu/en/simulation/nuclear-fission).

Using Radioactive Decay to Understand Earth Processes

How old is the Earth? How long ago did human civilizations arrive in California? How long has this boulder been exposed at the Earth's surface? Practically any time scientists want to know about the age of events older than the written historical record, they turn to radioactive decay to help them find out. This section shows how students can **apply their model [SEP-2]** of microscopic radioactive decay to answer such real-world questions. None of the PE's related to radiometric dating require that students can perform calculations of decay rates. The emphasis is instead on a qualitative model of the radiometric dating process and, more importantly, on the **analysis [SEP-4]** of results from radiometric dating to identify **patterns [CCC-1]** that provide **evidence [SEP-7]** of processes shaping Earth's surface.

When an atom has an unstable nucleus, it will undergo decay at a random time. Different elements behave differently as the number protons and neutrons in a nucleus affects the probability that an atom will decay in a certain time period, but it is not possible to predict when any given nucleus will decay. Science usually strives to find

cause and effect [CCC-2] relationships to predict when future events will occur, but having decay being largely based on fixed probabilities means that it is not sensitive to external triggers (at least under most natural conditions). Scientists have learned to calibrate radiometric clocks by measuring the proportion of radioactively unstable atoms (often called ‘parent products’) to stable products that are produced following decay (so-called ‘daughter products’). In a simple system of pure uranium-235 (a nucleus with 92 protons and 143 neutrons), about 50 percent of the atoms will have decayed after 700 million years (defined as its ‘half-life’). This probability has been calculated from much shorter observations of radioactive decay in laboratories. By contrast, pure carbon-14 (a nucleus with 6 protons and 8 neutrons) decays at a much faster rate with 50 percent of the atoms decaying into nitrogen-14 within just 5,730 years. Students can visualize what is meant by half-life using a computer simulation (see PhET, Radioactive Dating Game at https://phet.colorado.edu/en/simulation/radioactive-dating-game) or classroom activity with pennies representing individual atoms that ‘decay’ as they flip from heads to tails (Center for Nuclear Science and Technology Information of the American Nuclear Society, Half-Life : Paper, M&M’s, Pennies, or Puzzle Pieces: http://www.nuclearconnect.org/in-the-classroom/for-teachers/half-life-of-paper-mms-pennies-or-puzzle-pieces), or even using a physical model of ice melting (Wise 1990).

Real materials on earth rarely involve pure chunks of Uranium-235, Carbon-14, or any other radioactive parent product. There are initial amounts of other types of atoms, including daughter products. A rock can be thought of as a **system [CCC-4]** with parent and daughter products, but this system may not be closed and a portion of the daughter product may escape. Having ‘extra’ or ‘missing’ daughter products would alter the calculated age, if not properly recognized. Scientists have developed sophisticated tests involving comparisons of multiple parent-daughter systems to account for these issues and ensure accurate date measurements.

Scientists use these radiometric clocks to calculate the age of natural materials and learn about the past. Using data collected by geologists, students can compare the concentration of radioactive elements in different samples from Earth’s rocks, meteorites that have crashed into Earth’s surface, and moon rocks. Meteorites have compositions similar to what we expect the core of the Earth to look like, and are therefore interpreted to be pieces of other planetary objects that formed around the same time as Earth's core. Students can **calculate [SEP-5]** and **compare [SEP-4]** the age of these samples (see Keyah Math Project. "Keyah Math Module 8, Level 2: Age of the Earth" at http://keyah.asu.edu/lessons/AgeOfEarth/KM8.html). Many of these meteorites have similar ages of around 4.5-4.6 billion years and none have been found with ages older than that. Ages on the Moon are also similar, though a bit younger (4.4-4.5 billion years old). Students can use all this information as **evidence [SEP-7]** for making a claim about the age of Earth itself and use information about the age of the Moon to construct an account of the timing and possible mechanism by which it formed (*HS-ESS1-6*). A detailed assessment task for this PE was written by the authors of NGSS as a model of how the three-dimensional learning appears in the classroom (see Achieve, Unraveling Earth's Early History - High School Sample Classroom Task at http://www.nextgenscience.org/sites/default/files/HS-ESS_EarlyEarth_version2.pdf).

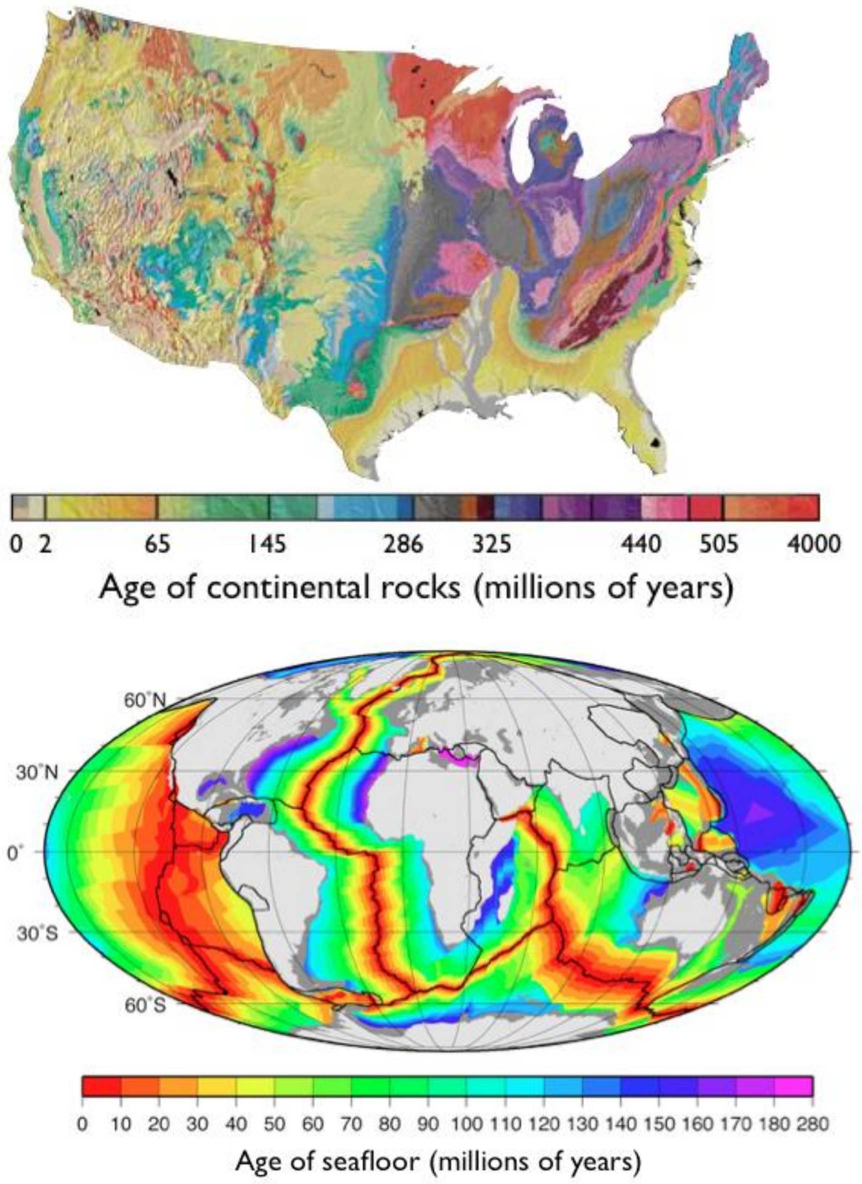
Since Earth formed, its surface has been constantly reshaped. We know this, in part, due to evidence from radiometric dating. Plate tectonics is one process that actively moves and deforms rocks, and students **analyzed [SEP-4]** a range of data types supporting this theory at the middle grade level (MS-ESS2-3). Now, students evaluate the theory to see if it is consistent with evidence from rock ages calculated using radiometric dating. They use evidence from rock ages to refine their model of the processes that shape earth's landforms (HS-ESS2-1).

The oldest individual minerals in some of Earth's oldest rocks are about 4.4 billion years old, though these rocks form only a tiny fraction of the planet's surface. Few rock formations are older than even three billion years, and those rocks are only found on the continents. The spatial distribution of the ages of rocks on continents has complicated **patterns [CCC-1]**. For example, some of the oldest rocks in California are located just outside the Los Angeles area in the San Gabriel Mountains. These rocks formed 1.8 billion years ago and are literally touching rocks just 85 million years old. This jumble of ages is evidence of California's complicated geologic history where faults slice up rock formations and move them across the state. Some might be surprised to find that the rest of the US does not appear that much different (top of figure 7.54). In fact, all continents show evidence of very complicated geologic histories where rocks of very different ages are mixed as continents are built up by the collision of smaller pieces and then broken back apart by later episodes of motion in a different direction. Students can observe maps of different rocks in California or North America (see USGS, The North America Tapestry of Time and Terrain." *Geologic Investigations Series* I-2781 at http://pubs.usgs.gov/imap/i2781/) and **ask questions [SEP-1]** about the **patterns [CCC-1]** they notice. Why do the patches of color take up so much space in the eastern half of the continent while the western US looks much more speckled with color? Why are there no metamorphic rocks in the middle of the country? Why does Florida have so many young rocks?

Measurements of the seafloor age, however, are much younger (no rock being older than 280 million years) and show a clear pattern. We know that there must have been oceans older than 280 million years ago because we have found fossil marine creatures in rocks that date back much older than that found on today's continents. So what happened to the rest of the old seafloor? A clue comes from the fact that ages typically progress in a logical order in a symmetric **pattern [CCC-1]** from the middle of the ocean outwards (bottom of figure 7.54).

Students should be able to use data from radiometric ages to collect evidence that the crust is moving (HS-ESS1-5). Running along the center of the ocean is a band of rock with zero age. This means that there is no accumulated daughter product from radioactive decay (above the background level). How can this be when the unstable parent isotopes are present and therefore constantly decaying into the daughter products? When rock is hot, atoms can move around relatively easily and daughter products for radioactive decay can therefore escape or equilibrate with the background concentration of that element. As a rock cools, atoms are locked into their positions in crystal lattices; this is the moment when the geologic clock starts ticking. The new crust in the center of the ocean was therefore very hot in the recent past, which is evidence that it rose up from Earth's interior. As new crust is progressively forming, it also must move constantly away from middle of the ocean. At the same time, older crust must therefore be sinking down (which would be expected as the crust becomes denser as it cools over time, and explains why there are no older seafloor ages). Since students can measure the distance of crust from the mid ocean and know its age at different points, they can **calculate [SEP-5]** how quickly the crust is moving in different ocean basins and even how those rates have changed over geologic history. Do ocean basins with faster moving seafloor experience more earthquakes each year?

Figure 7.54. Rock Ages in the Continental US and Seafloor



Map of rock ages in the continental US (top) and seafloor (bottom). Continental rocks are as old as 4 billion years and are a jumbled mix of ages. Seafloor rocks show a consistent pattern and are never older than 280 million years. Sources: Adapted from Vigil, Pike, and Howell 2000; National Oceanic and Atmospheric Administration, National Centers for Environmental Information 2008a.

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. IS5 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: 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-PS4-3. 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 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.]**

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-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)

*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	**PS4.A: Wave Properties**	[CCC-1] Patterns
[SEP-2] Developing and Using Models	**PS4.B: Electromagnetic Radiation**	[CCC-3] Scale, Proportion, and Quantity
[SEP-3] Planning and Carrying Out Investigations	**PS4.C: Information Technologies and Instrumentation**	[CCC-5] Energy and Matter: Flows, Cycles, and Conservation
		[CCC-7] Stability and Change

[SEP-4] Analyzing and Interpreting Data **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-7] Engaging in Argument from Evidence** **[SEP-8] Obtaining, Evaluating, and Communicating Information**	**PS3.D: Energy in Chemical Reactions** **ETS1.A: Defining and Delimiting Engineering Problems**	**-------------------------** **Interdependence of Science, Engineering, and Technology** **Influence of Science, Engineering, and Technology on Society and the Natural World**

CA CCSS Math Connections: A-SSE.1a-b,3a-c; A-CDE.4; N-Q.1-3; MP.2; MP.4
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a
CA CCSS ELA/Literacy Connections: SL.11-12.5; RST.9-10.8; RST.11-12.1,7, 8; WHST.9-12.2.a-e, 8

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 IS, 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.

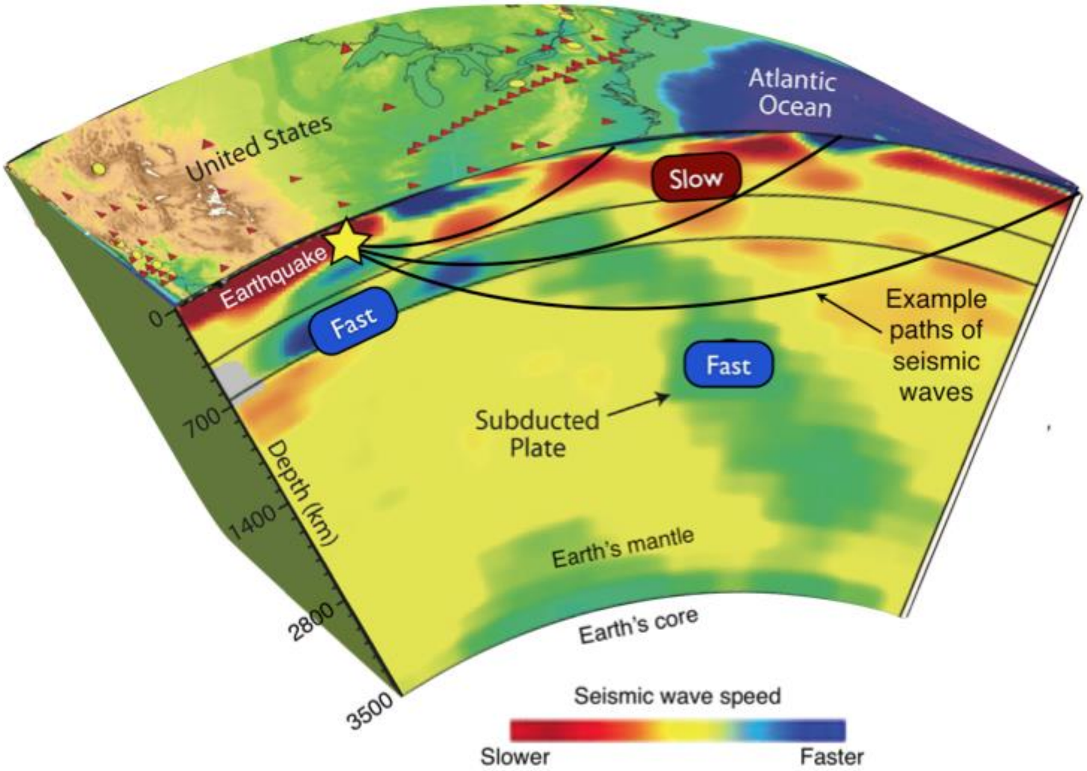
At the high school level, students can describe a wave as a disturbance or oscillation that transmits energy without transmitting matter. Mechanical waves travel through a medium, temporarily deforming the material. Restoring forces caused by elastic properties in the medium then reverse this deformation. 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 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 do 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 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). 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.

High School Physics in the Universe Vignette 7.3: Seismic Waves

Performance Expectations

Students who demonstrate understanding can:

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-PS4-5. 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-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-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.]**

Highlighted Science and Engineering Practices	**Highlighted Disciplinary Core Ideas**	**Highlighted Crosscutting Concepts**
[SEP-1] Asking Questions and Defining Problems	**PS4.A: Wave Properties**	**[CCC-1] Patterns**
[SEP-2] Developing and Using Models	**PS4.C: Information Technologies and Instrumentation**	**[CCC-3] Scale, Proportion, and Quantity**
	ESS2.B: Plate	**-------------------------**

[SEP-3] Planning and Carrying Out Investigations **[SEP-4] Analyzing and Interpreting Data** **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-8] Obtaining, Evaluating, and Communicating Information**	**Tectonics and Large-Scale System Interactions** **ESS3.A Natural Resources** **ESS3.B Natural Hazards**	**Influence of Science, Engineering, and Technology on Society and the Natural World** **Science Addresses Questions About the Natural and Material World**

CA CCSS Math Connections: F-BF.1; N-Q.1-3; MP.2; MP.4*; G-CO.1, G-CO.12, G-C.5*
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a
CA CCSS ELA/Literacy Connections: SL.11-12.4; RST.9-10.8; RST.11-12.1,7,8;

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 IS 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.

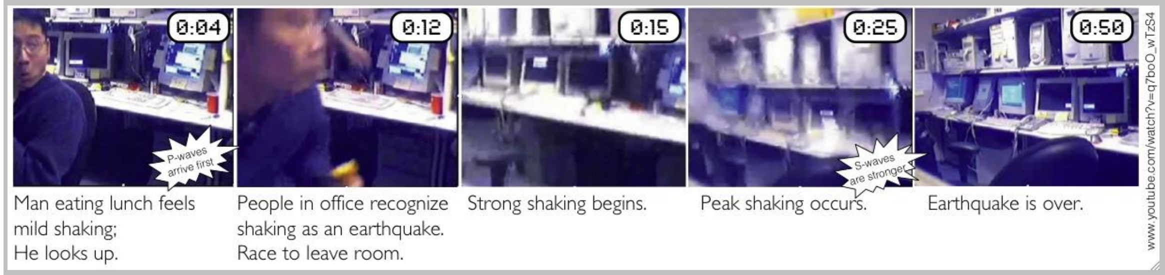
Day 1: Observing earthquakes Students observe recordings of seismic waves and relate them to what earthquakes feel like.	**Days 2-3: Earthquake Early Warning Systems: Longitudinal and Shear Waves in the Earth** Students model earthquake waves in a slinky and with their bodies to show how they could design 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

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 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. 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 (figure 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 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 (figure 7.57).

Figure 7.57: Measurements of an Earthquake from Different Locations

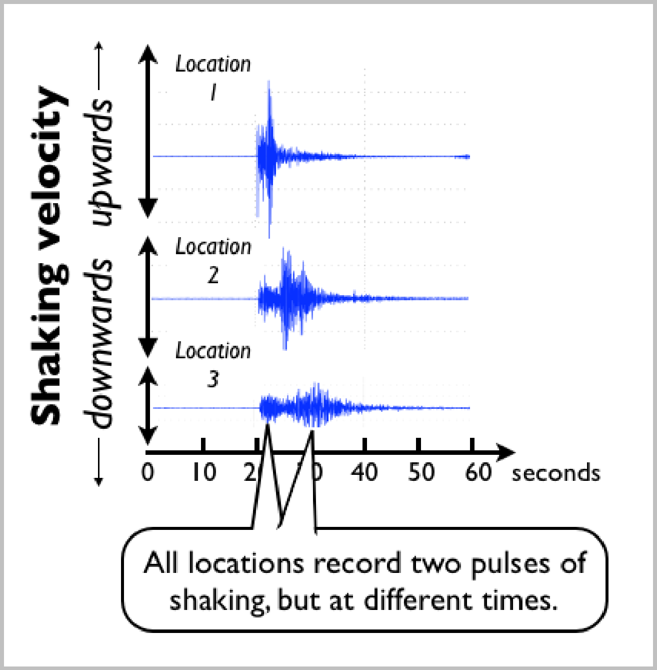


Diagram by M. d’Alessio

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 [SEP-1]** 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 [CCC-3]**). “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 seismograms and notice that the amplitude of the shaking is different. Evan **asks [SEP-1]** 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.

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

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 [SEP-8]** an **explanation [SEP-6]** about why the two pulses of energy arrive at different times at different locations (figure 7.58). Their examples show that the two waves travel at different speeds.

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

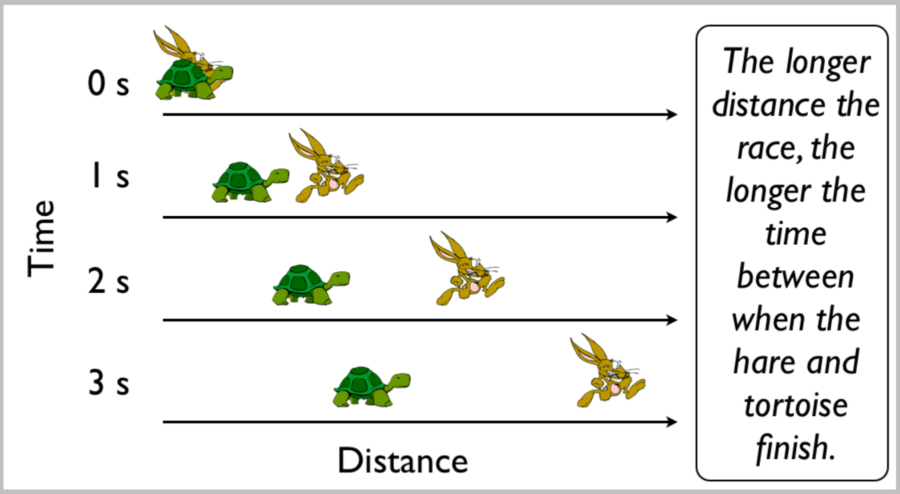


Diagram by M. d’Alessio

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

In an earthquake, people can certainly feel 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 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 can 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 foreshadows that they will discuss the topic a lot more in a few days.

Mr. J demonstrates waves using a physical **model [SEP-2]**, 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 (see IRIS, Seismic Slinky at http://www.iris.edu/hq/inclass/video/seismic_slinky_modeling_p_and_s_waves_in_the_classroom). The waves go by very quickly on the spring, so Mr. J has 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.iris.edu/hq/inclass/demo/human_wave).

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 [CCC-1]** 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 [SEP-4]** 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?

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 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 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. This might be parallel your experience watching a distant lightning storm – 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 [SEP-2]** 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 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

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

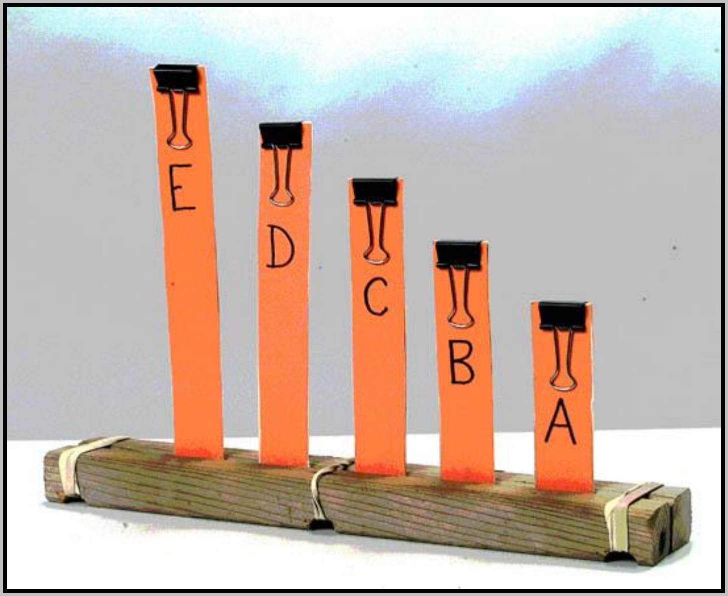
Earthquake early warning works because information from seismic recording stations in many different locations can send their measurements to a central data processing facility instantly. In order to avoid costly false alarms or failing to issue a warning about a damaging earthquake, the information must be transmitted reliably. Mr. J tells students that they will develop a technique for transmitting the shaking history shown by their seismogram to students on the 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 an 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

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

Mr. J starts 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, https://youtu.be/9X-js9gXSME). 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 [SEP-2]**. They will 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.iris.edu/hq/inclass/demo/demonstrating_building_resonance_using_the_simplified_boss_model). 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 (figure 7.59).

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



Source: IRIS 2014

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 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 [CCC-1]** 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.
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 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 [SEP-2]** 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 [SEP-5]** 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 (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 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 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 shows video clips with the results of computer simulations of famous California earthquakes (see USGS, Computer Simulations of Earthquakes for Teachers at http://earthquake.usgs.gov/regional/nca/simulations/classroom.php). 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 (see AGU, Watch the ground ripple in Long Beach, http://blogs.agu.org/tremblingearth/2012/12/17/watch-the-ground-ripple-in-long-beach/). 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.

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 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 do not 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.

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

Mr. J returns to the physical **model [SEP-2]** 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 cannot visually see any consistent **patterns [CCC-1]** 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 (see D. Brown Tracker video analysis and modeling tool from

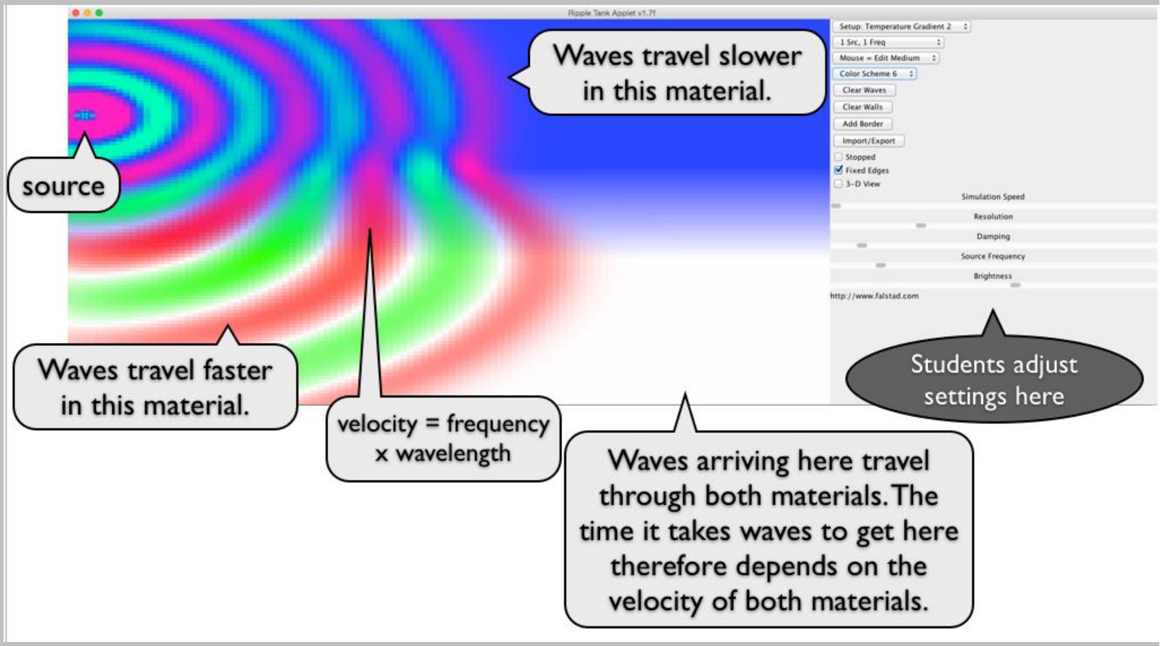
2015 at http://physlets.org/tracker/) so that they can watch it in slow motion and measure and compare the speed of the waves in several sample earthquakes. When students **analyze the data [SEP-4]**, they find that the speed the waves traveled was **proportional [CCC-3]** to the length of the spring 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 [SEP-6]** 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 [SEP-2]** 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 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 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.

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

Mr. J has students open up a free computer simulation to **investigate [SEP-3]** waves moving through a medium (see Ripple Tank at http://www.falstad.com/ripple/). The simulator **models [SEP-2]** 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 [SEP-8]** their understanding of what it shows about wave behavior. Mr. J walks around interacting with each group, encouraging them to **ask questions [SEP-1]** 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 (figure 7.60). “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 asks students to estimate which material has a faster wave velocity (HS-PS4-1).

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



Setup: Temperature Gradient 2
1 Src, 1 Freq
Mouse = Edit Medium
Color Scheme 6
☐ Stopped
☑ Fixed Edges
☐ 3-D View

Diagram by M. d’Alessio

Mr. J wants students to use their **mathematical thinking [SEP-5]** 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 [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 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 [SEP-8]** 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

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

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 [SEP-2]** of Earth's interior from IS4 (*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 (*CA CCSS MN-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 (*CA CCSSMG-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 n.d.)

Vignette Debrief

Using earthquakes to motivate the study of waves allows 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]** 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 [SEP-5]** 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 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 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 [SEP-4]**, usually using their smartphones or other technology to submit their data so that the whole class can see **patterns [CCC-1]** instantly. The PE's 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 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 (PS4.A). Seismic recording devices are a key technology discussed throughout the IS, and there is explicit attention to how these systems are 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 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 (PS2.A) with wave resonance. Both earthquake early warning and earthquake engineering are key concepts where science and engineering can benefit society by saving lives (ETS2.B). 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 (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 does 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 participate in small group and whole class discussions (SL.11-12.1a-d). The students also produce 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 calculates the amount of time it will take waves to travel through the planet, assuming that the waves travel at a constant speed (*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 (*CA CCSSM G-CO.1, G-CO.12, G-C.5*).

Resources

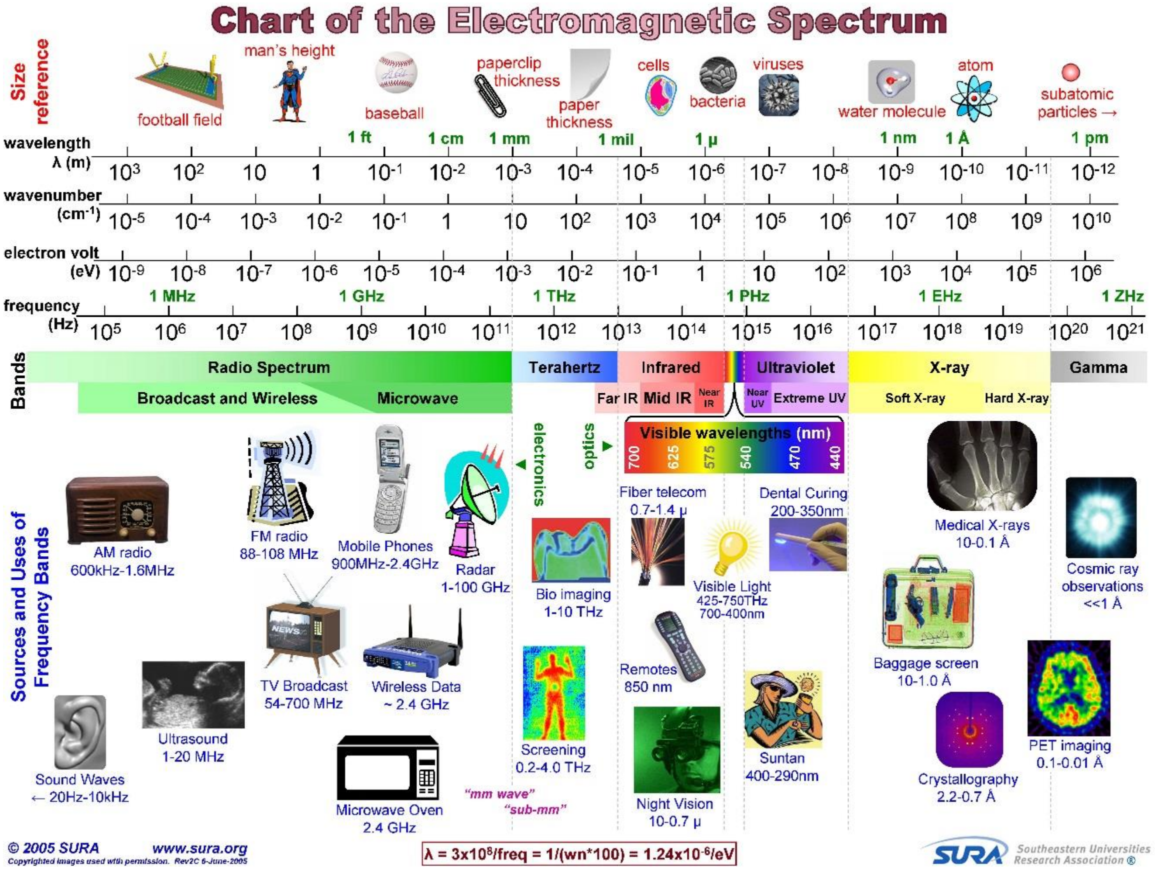
California State University Northridge. n.d. Earthquake Early Warning Simulator. http://www.csun.edu/quake (accessed August 12, 2016).

Rapid Earthquake Viewer. n.d. http://rev.seis.sc.edu/ (accessed August 12, 2016).

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 haves 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 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 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 [CCC-5]**. 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 [SEP-7]** that supports the claim 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 evidences for the particle nature of light is the photoelectric effect, the observation that many metals emit electrons when light shines upon 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., 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 table top 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 have examined electromagnetic radiation. Does it have possible health impacts as well? Students know that they can get sunburnt 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. 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 PE, 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) is 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 not receive a sunburn, so microwaves with even lower energy photons. Just like in the photoelectric effect, these 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://undsci.berkeley.edu/article/0_0_0/sciencetoolkit_01) 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' where 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: decoding wave interactions with mediums, and encoding our own signals on them. 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 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 [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 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 [SEP-4]** 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 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.

Physics in the Universe – Instructional Segment 6: Stars and the Origins of the Universe

From the NGSS storyline:

> *High school students can examine the processes governing the formation, evolution, and workings of the solar system and universe. Some concepts studied are fundamental to science, such as understanding how the matter of our world formed during the Big Bang and within the cores of stars. Others concepts are practical, such as understanding how short-term changes in the behavior of our sun directly affect humans. Engineering and technology play a large role here*

in obtaining and analyzing the data that support the theories of the formation of the solar system and universe. (NGSS Lead States 2013d)

Physics in the Universe – Instructional Segment 6: Stars and the Origins of the Universe

Guiding Questions:

- How do we know what are stars made out of?
- What fuels our Sun? Will it ever run out of that fuel?
- Do other stars work the same way as our Sun?
- How do patterns in motion of the stars tell us about the origin of our Universe?

Performance Expectations

Students who demonstrate understanding can:

HS-ESS1-1. Develop a model based on evidence to illustrate the life span of the sun and the role of nuclear fusion in the sun's core to release energy in the form of radiation. **[Clarification Statement: Emphasis is on the energy transfer mechanisms that allow energy from nuclear fusion in the sun's core to reach Earth. Examples of evidence for the model include observations of the masses and lifetimes of other stars, as well as the ways that the sun's radiation varies due to sudden solar flares ("space weather"), the 11-year sunspot cycle, and non-cyclic variations over centuries.] [Assessment Boundary: Assessment does not include details of the atomic and sub-atomic processes involved with the sun's nuclear fusion.]**

HS-ESS1-2. Construct an explanation of the Big Bang theory based on astronomical evidence of light spectra, motion of distant galaxies, and composition of matterin the universe. **[Clarification Statement: Emphasis is on the astronomical evidence of the red shift of light from galaxies as an indication that the universe is currently expanding, the cosmic**

microwave background as the remnant radiation from the Big Bang, and the observed composition of ordinary matter of the universe, primarily found in stars and interstellar gases (from the spectra of electromagnetic radiation from stars), which matches that predicted by the Big Bang theory (3/4 hydrogen and 1/4 helium).] HS-ESS1-3. Communicate scientific ideas about the way stars, over their life cycle, produce elements. **[Clarification Statement: Emphasis is on the way nucleosynthesis, and therefore the different elements created, varies as a function of the mass of a star and the stage of its lifetime.] [Assessment Boundary: Details of the many different nucleosynthesis pathways for stars of differing masses are not assessed.]**
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-3] Planning and Carrying Out Investigations**	**ESS1.A: The Universe and Its Stars** **PS1.C: Nuclear Processes**	**[CCC-1] Patterns** **[CCC-2] Cause and Effect** **[CCC-3] Scale, Proportion, and Quantity**

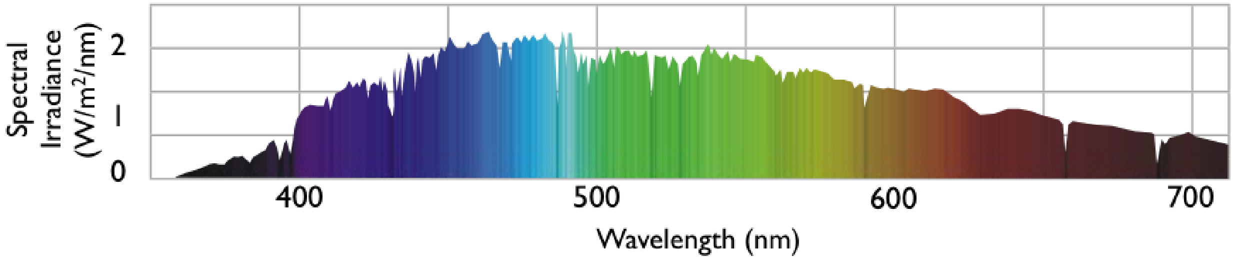
[SEP-4] Analyzing and Interpreting Data **[SEP-5] Using mathematics and Computational Thinking** **[SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering)** **[SEP-7] Engaging in Argument from Evidence** **[SEP-8] Obtaining, Evaluating, and Communicating Information6]**		**[CCC-4] System and System Models** **[CCC-5] Energy and Matter: Flows, Cycles, and Conservation** **[CCC-6] Structure and Function** **[CCC-7] Stability and Change**
CA CCSS Math Connections: N-Q.1-3; A-SSE.1a-b; A-CED.2,4; MP.2; MP.4		
CA ELD Connections: ELD.PI.11-12.1,5,6a-b,9,10,11a		
CA CCSS ELA/Literacy Connections: SL.11-12.4; RST.11-12.1; WHST.9-12.2.a-e		

Students now apply their understanding of electromagnetic radiation to studying the light from stars. Teachers can start this IS the same way humans have for millennia – looking up in the sky and wondering what is in the heavens. In a classroom, students can zoom in and out to explore the “maps” of the stars and galaxies in space (such as the Sloan Digital Sky Survey at SDSS DR12 Navigate Tool, http://skyserver.sdss.org/dr12/en/tools/chart/navi.aspx) to engender interest in what is out there, and to get a basic sense that the Universe is a varied place, with dense and less dense regions of stars and gas distributed throughout it. Students discuss and share their favorite astronomical pictures and communicate to others about what they see.

The Colors of Stars

Looking carefully, students notice different stars have slightly different colors – those differences reveal a huge amount about what stars are and the way they work. When viewing the rainbow of light from our Sun through a prism, some colors appear brighter than others (figure 7.62). What causes these variations? Are they the result of errors in the equipment, something peculiar about our Sun, or a common feature of stars? Like all good science, this general observation with the naked eye can be refined with detailed measurement of specific **quantities [CCC-3]** such as the intensity of light at each wavelength (a ‘color spectrum’). Students can **obtain [SEP-8]** color spectra from many different stars using an online tool (such as the Sloan Digital Sky Survey, What is Color at http://skyserver.sdss.org/dr1/en/proj/basic/color/whatiscolor.asp) and **compare them [SEP-4]**, noticing several important **patterns [CCC-1]**. These patterns give clues about the **cause [CCC-2]** of different phenomena.

Figure 7.62. Color Spectrum of Our Sun

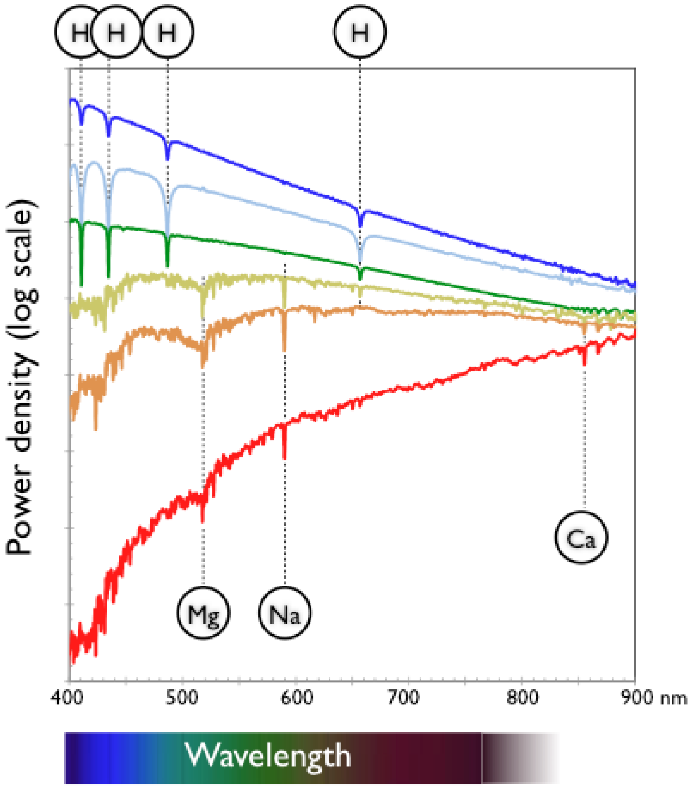


Color spectrum of our Sun. The rainbow image and the height of the graph depict the same information. The rainbow image is created by splitting the light from a telescope with a prism. The values of the graph are measurements of the relative intensity of each color. The graph dips lower where the rainbow image is dimmer. Diagram by M. d'Alessio.

Students notice that many stars have bands of low intensity at the exact same wavelength (figure 7.63). Understanding this observation requires additional background in physical science. The *NRC Framework* lays out strong connections between the DCIs in this IS and physical science:

> *The history of the universe, and of the* ***structures [CCC-6]*** *and objects within it, can be deciphered using observations of their present condition together with knowledge of physics and chemistry.* (National Research Council 2012, 173).

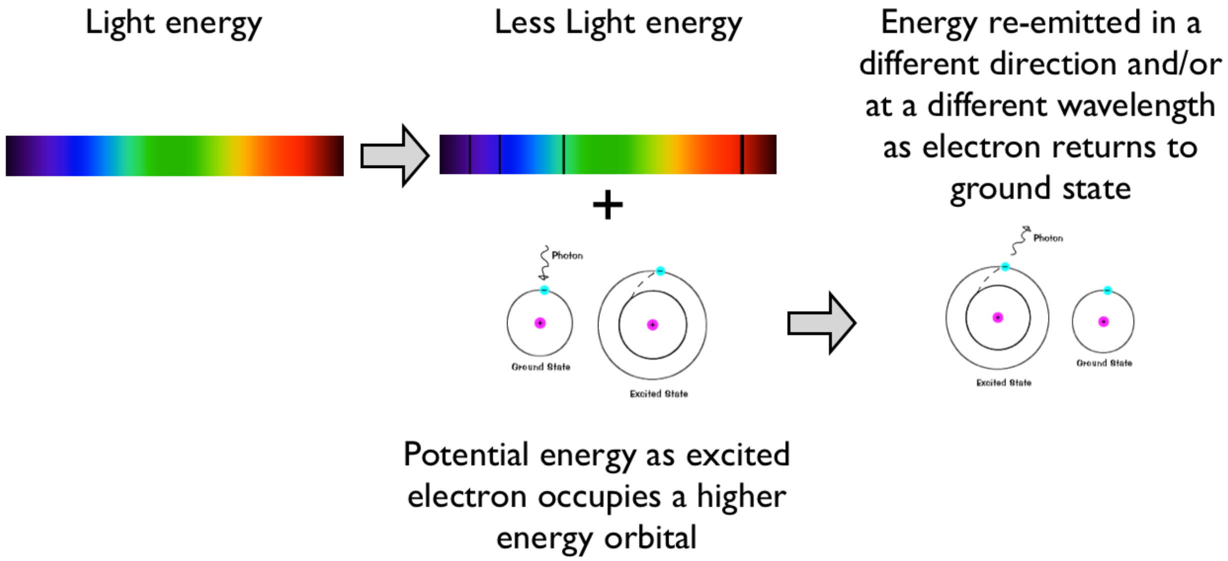
Figure 7.63. Spectra of Six Different Stars



Circles indicate spectral lines from different elements on the periodic table. Diagram by M. d'Alessio with data from Sloan Digital Sky Survey n.d.

The concept of absorption lines in spectra from stars unites the study of matter and the study of waves. Students build upon their **model [SEP-2]** of the structure of atoms from IS4 (PS1.A; HS-PS1-8) and that light is a name for one segment of the electromagnetic spectrum (IS5; PS4.B; *HS-PS4-1*). The dark bands common in star spectra occur because atoms of different elements absorb specific colors of light (figure 7.64). Students have studied energy conversion as early as grade four and throughout the grade spans (PS3.B: *4-PS3-4, MS-PS3-3, 4, 5, HS-PS3-3; IS3*), and now they must consider a very sophisticated example of individual atoms working as tiny **energy [CCC-5]** conversion devices. Atoms absorb some of the light energy (or other energy from the electromagnetic spectrum) that hits them, which pushes electrons to higher energy levels than their normal 'ground state' and temporarily stores the energy as a potential energy. The atom quickly converts the energy back to light energy to return to its ground state, but that energy may be emitted in a completely different direction than the original energy or may be at a different wavelength. Each element on the periodic table has a unique electron orbital configuration, so different elements absorb light energy at very specific colors (wavelengths). Students can therefore use the absorption bands as ‘fingerprints’ to identify the types and relative quantity of elements in a given star. Figure 7.63 shows that common star spectra include fingerprints of a number of elements, and more detailed analysis allows scientists to determine the full range of elements and even their relative abundance to construct the complete chemical composition of a star’s atmosphere. In order for students to be able to **explain [SEP-6]** this multi-step process, the class could act out the process using their bodies to represent different components of the **system [CCC-4]** in a physical **model [SEP-2]**. Using the language of **systems [CCC-4]** helps focus student attention on the energy inputs (light), the internal workings of the system (electrons in different energy level orbitals), and the energy outputs (light emitted in a different direction or at a different frequency than the energy input).

Figure 7.64. A Model of Absorption Lines



Absorption spectra occur because individual atoms can temporarily convert light energy into potential energy. Diagram by M. d’Alessio with images from Wereon 2006 and NASA 2010.

The absorption of specific wavelengths of electromagnetic waves occurs in stars, but also all around on Earth, including greenhouse gases in Earth's atmosphere. Elements like CO_2 and water vapor absorb infrared energy heading away from the planet and re-emit it back towards Earth so that energy that would have otherwise have left the system is retained. This process is fundamental to Earth's energy balance as discussed in the high school Chemistry in the Earth System course (*HS-ESS2-4*).

Evidence for Fusion

For ages, scientists have pondered what has caused the Sun to shine. In 1854, William Thomson (who later became so well known as a scientist that he was knighted and now is known as Lord Kelvin) published a paper calculating that the Sun would run out of fuel completely in just 8,000 years if it were made entirely of gunpowder (the most energy-dense self-contained fuel he could think of at the time) (Kelvin 1854). Even in the 1850s, geologists had evidence that the Earth is considerably older than that, so controversy ensued over what causes the Sun to shine.

Lord Kelvin correctly determined that no chemical reaction would yield enough energy to power the Sun, but he incorrectly concluded that the Sun must be getting a constant replenishment of energy from meteors that collide with it. He died in 1907, more than a decade before scientists discovered a process that could release previously inconceivable amounts of energy, nuclear fusion (IS4). Under most conditions, when two atoms collide they bounce off one another because of the repulsive forces between their nuclei. If the atoms are moving fast enough, collisions can bring their nuclei enough together that they fuse, releasing more than a million times more energy per unit of mass than any chemical reaction.

Students can repeat Lord Kelvin's **calculation [SEP-5]** about how long the Sun can last if it continues to emit energy at its current rate, but this time using information he did not have about the composition of the Sun from spectral lines (not gunpowder, but 75 percent hydrogen) and the energy release of hydrogen fusion (instead of chemical reactions). This approximate calculation of the **scale [CCC-3]** of energy release shows that the Sun's lifetime will be on the order of several billion years. Students can **support or refute the claim [SEP-7]** that this result is reasonable, using evidence of the age of the Earth from IS4.

Opportunities for ELA/ELD Connections

Students select and read a biography about or autobiography/memoir by a famous or influential scientist known for his/her work about the stars, Sun, planets, or Universe. (Note: The teacher may provide a list of names to select from to ensure certain concepts are highlighted.) They select one question they have about the topic, and citing evidence from text, write a letter to the scientist that conveys critical concept, knowledge, or discovery by the scientist, identify relevant or key idea, or other words/phrases relevant to the topic, and a relevant question they have for the author that is supported by evidence from text related to the topic.

CA CCSS ELA/Literacy Standards: RST.9–12.2, 4, 8; SL. 9–12.4, 5

CA ELD Standards: ELD.PI. 9–126, 10

A Model of Fusion in Stars Over Their Lifecycle

In order for fusion to occur, atoms must reach to a high enough temperature that they move fast enough to fuse together, typically millions of degrees. Such temperatures do not occur naturally anywhere on Earth – they only happen in the interiors of stars where temperatures and pressures are so high due to gravity and the kinetic energy of in falling matter. But even at the center of a star, conditions can **change [CCC-7]** that cause fusion to start and stop. As a result, we say that stars are born and die.

Stellar Birth and Activating Fusion

A star begins its life as a cold cloud of dust and gas. Gravity attracts the individual dust and gas particles and they fall towards one another, decreasing the gravitational potential **energy [CCC-5]** of the **system [CCC-4]**. Since energy must be conserved in the system, the particles gain kinetic energy (much like a ball falling downward speeds up as it gets lower). The temperature of an object is a measure of the average kinetic energy of its molecules, so we say that the star warms up as it contracts. At some point, the particles may be moving fast enough that they undergo nuclear fusion when they collide. Within the same cloud of dust and gas, many objects can form simultaneously. Objects that accumulate enough mass to start fusion are called stars. Planets are made of the exact same material as stars and accumulate by the exact same gravitational processes, but their mass is not sufficient to begin fusion.

Mid-life as a Star: a Balance

Once fusion begins, the **energy [CCC-5]** it releases causes particles to push one another apart and the star begins to expand again. This is the opposite situation as the original star formation and involves an increase in gravitational potential energy that must be balanced by the particles slowing down (much like a ball thrown upward slows down as it gets higher). At slower speeds, fusion is less likely to occur and the star stops expanding. This counterbalancing[1] feedback between the explosive force of fusion and the attraction due to gravity keeps stars **stable [CCC-7]** during most of their lifespan (figure 7.65). This stable period of a star's life is referred to as the main sequence and it means that hydrogen is fusing in the star's core.

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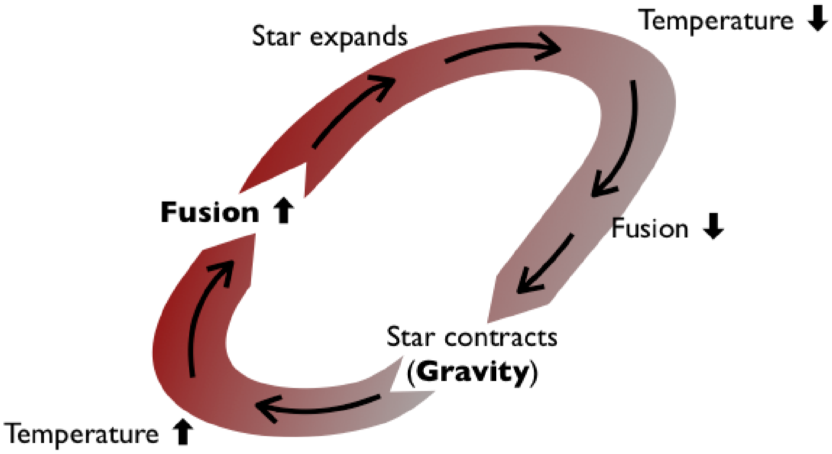
[1] In the CA NGSS standards and many textbooks, these feedbacks are called 'negative' feedbacks. This *CA Science Framework* uses 'counterbalancing' because many counterbalancing feedbacks have very favorable effects.

Figure 7.65. Counterbalancing Feedback in Stars



The explosive force of fusion balances the attractive force of gravity keeping stars **stable [CCC-7]** during most of their lives. Diagram by M. d'Alessio.

Growing Older

Even the core of a young star is not typically hot enough to fuse anything except hydrogen. Larger stars burn it more quickly because they are a higher temperature, and all stars eventually fuse all the hydrogen in their core into helium, so fusion stops (marking the end of the period called the main sequence). Without fusion pushing the star outward, the counterbalancing feedback shown in figure 7.65 becomes unbalanced, and then gravity acts alone to contract the star.

Contraction causes temperature increases in both the core and the surrounding envelope. If the star has enough mass, it may heat enough for helium atoms to begin fusing together. If that helium gets used up, the same processes will create, in sequence, large elements up to the size of iron. Only stars that start off their lives with a large enough mass are able to generate elements larger than helium during their lifetimes. Contraction of the star's envelope triggers hydrogen to begin fusing there. The outer envelope is less dense, so gravity does not act as effectively to hold the star together and fusion in the envelope causes the star to expand to a massive size, which is why some stars are called "giants" and "supergiants."

Our Sun is currently in its main sequence, so it has not yet been a giant and still only fuses hydrogen in its core. So how does it get all the more massive elements than helium that show up in its spectra? Where did they come from?

The End of Stars

Once hydrogen fusion stops in the Sun's core, hydrogen fusion in its envelope will cause it to grow to be a giant star. Eventually its envelope will expand away and leave behind a core made primarily of carbon and oxygen. That core will still be incredibly hot and it will continue to glow for a long time even without fusion. Some of the stars we see in the night sky are actually the hot, dying cores of stars that have finished fusion.

Larger stars continue fusing atoms until they end up entirely with iron in their cores and spontaneous fusion stops. The core is already very dense and gravity can cause the entire core to collapse within a few seconds. This rapid core collapse leads to such high temperatures and pressures that there is finally enough extra **energy [CCC-5]** to fuse elements larger than iron. Practically all of the atoms in the Universe larger than iron formed during the cataclysmic collapse of these large stars. The collapsing core rebounds in a dramatic explosion called a supernova, ejecting all of its material out into space where it can eventually coalesce into new stars. The carbon in our bodies came from carbon made in a star that exploded and was ejected into a region of space where our solar system was born. As Carl Sagan has said, "We are made of star-stuff."

Students combine their model of fusion (*HS-PS1-8*) with the counterbalancing feedback in figure 7.65 to construct a **model [SEP-2]** of how fusion relates to a star's lifecycle (HS-ESS1-1). They apply this model to a product that communicates how material got from the random hydrogen atoms inside a young star to the complex range of elements inside their own bodies (*HS-ESS1-3*). They create a diagram, storyboard, movie, or other product that illustrates this step-by-step sequence. At each stage of their diagram, they should be able to answer the question, "What is the evidence that this particular stage happens?"

High School Physics in the Universe Snapshot 7.14: Asking Questions About Patterns in Stars

Investigative phenomenon: Bright stars can be located near or far from Earth but they are typically hotter.

Students review a table of a number of properties of the 100 nearest stars and the 100 brightest stars using a spreadsheet (figure 7.66). They construct graphs of different properties looking for **patterns [CCC-1]** in this data. They find that many of the factors, are uncorrelated ("It looks like bright stars can be located both near and far from us."), but they should see a definite pattern between brightness and temperature—hotter stars are brighter and colder stars are dimmer. They may begin with a linear **scale [CCC-3]**, but with such a large range in the brightness of stars (less than 1% as bright up to 100 times brighter than the Sun), they discover will need to adjust to a logarithmic **scale [CCC-3].**

Figure 7.66: How Does Star Brightness Depend on Temperature?

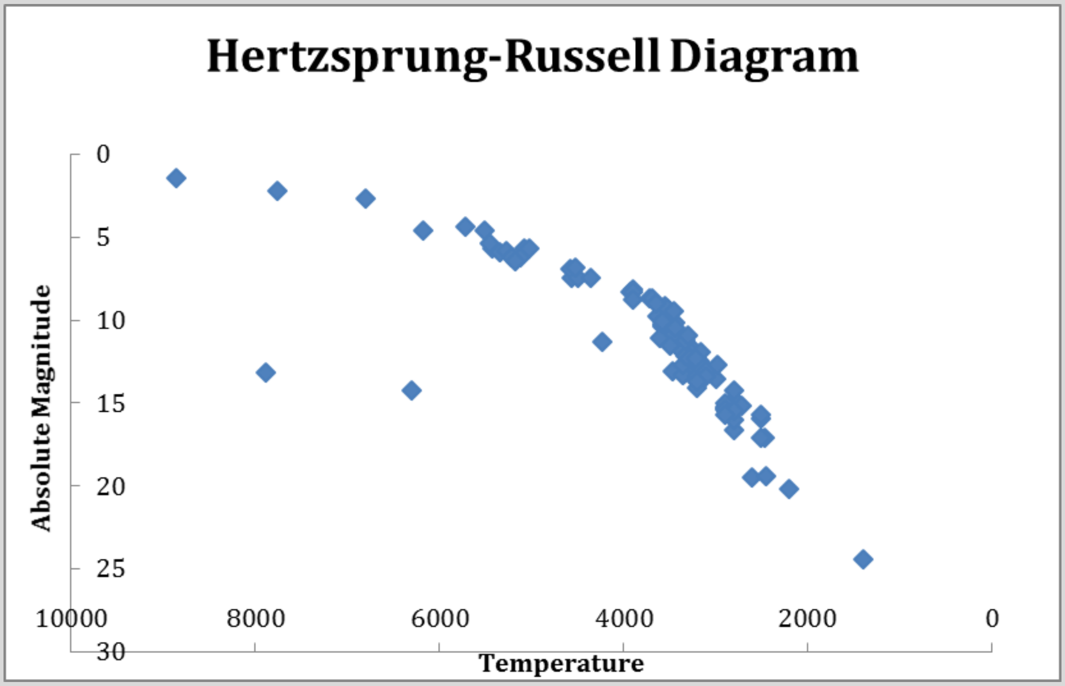


Diagram by M. d'Alessio

Anaya: Not all the bright stars are hot, though. Are those outliers?

Cole: And not all the dim stars are cold.

Ms. M.: Why do you think that is? Should we graph more data?

Jordan: Maybe those dim ones are farther away.

Diego: I don't think so. We graphed distance versus brightness and there wasn't any trend. But I'll look specifically at the data for those stars to make sure.

Jordan: Well maybe they're smaller then. If they're small, maybe they wouldn't be very bright even if they were hot.

Anaya: And maybe those cold ones would be bright if they were really big.

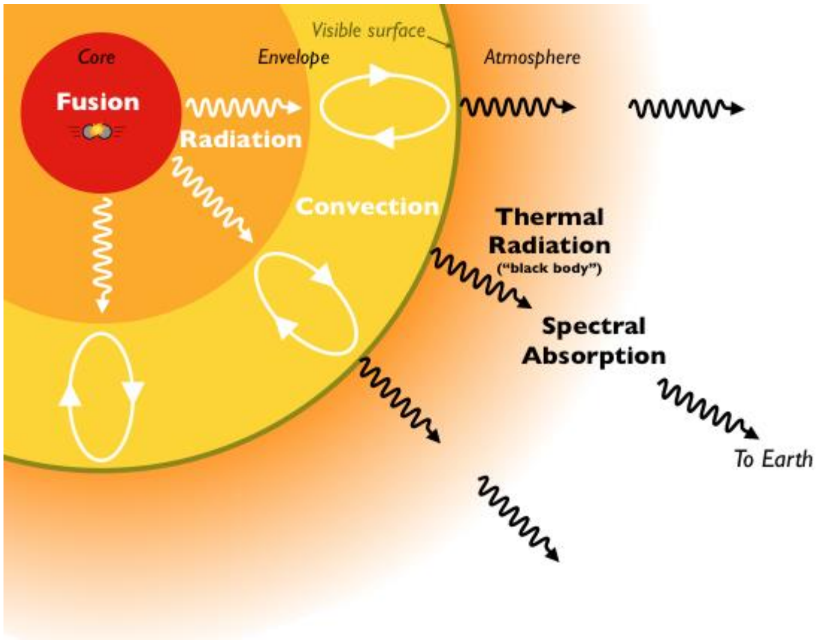
Students **ask questions [SEP-1]** that lead them to further investigation. The example student dialog is idealized, but effective talk moves can help structure conversations so that students move towards this ideal (as outlined in the instructional strategies chapter of this *CA Science Framework).*

This **pattern [CCC-1]** in the data was discovered by Ejnar Hertzsprung and Henry Russell around 1910 and is commonly referred to as a Hertzsprung-Russell (H-R) Diagram. It appears in several different forms including color or "spectral type" instead of temperature. Like the coals in a fire, cooler stars are red and hotter stars are orange, yellow, or even blue. (Several online simulations are available to allow students to explore this relationship between temperature and color.) Students can add this relationship to their model of the Sun's **energy [CCC-5]** emissions (*HS-ESS1-1*) because it helps explain the overall broad range of colors emitted by the Sun in figure 7.62. It relates to the star's lifecycle because most of the stars fall along the central diagonal line in the H-R diagram, which is referred to as the main sequence. As they move through their life cycle and stop fusing elements in their core, stars plot in different sections of the H-R diagram than they did during their main sequence.

Getting Energy to Earth

As early as grade five in the CA NGSS, students generate a model showing that most of the energy that we see on Earth originated in the Sun (*5-PS3-1*). Now students will expand their system **model [SEP-2]** to trace the **flow of energy [CCC-5]** back to fusion in the Sun's hot core (*HS-ESS1-1*). Students will need to use models of heat transfer within a system such as radiation and convection from physical science (*HS-PS3-4*). They develop a model of convection at Earth's surface at the middle grade level (*MS-ESS2-6*) and in Earth's interior in the high school Chemistry in the Earth System course, now they can apply it to the interior of the Sun. Convection occurs in a large section of the Sun's outer envelope, moving heat from the interior out to the visible surface (figure 7.67). Students can directly observe evidence of this convection in high resolution optical images of the sun's surface that look like a bubbling cauldron. This convection plays a role in the eruption of solar flares and other variations in solar intensity, which have been recorded for centuries (NASA 2003b). Some of these variations are periodic (the Sun's magnetic field flips about every 11 years, ***causing* changes [CCC-7]** in the amount of radiation of about 0.1 percent) while slightly larger variations are less well understood but can make a big difference in Earth's climate over much longer **timescales [CCC-3]** (from decades to millions of years). The existence of these variations is further evidence for convection, which constantly bubbles up new high temperature material that emits more **energy [CCC-5]** than the cooler and denser material that sinks down. Even though no fusion occurs on the visible surface, it still shines via a process known as thermal radiation (or "black body" radiation). Most of this radiation travels directly towards earth, but a small fraction of it is absorbed, creating the absorption spectra of figure 7.67.

Figure 7.67. Energy Transfer from the Sun to Earth



Energy transfer by radiation and convection moves energy from the Sun's core to Earth. There are a number of steps along the way. Diagram by M. d'Alessio

Origins of the Universe

Students **analyze [SEP-4]** spectra of stars beyond the Sun by comparing them to a set of known spectral lines of different elements determined in a laboratory. In order to match the laboratory lines, they find that they need to shift the star spectra. Understanding the significance of this observation requires understanding of the Doppler effect, a process that builds on students' existing models of waves but is not required to meet other CA NGSS PEs. When stars move towards or away from a viewer, the wavelength of their light shifts. We can therefore use the Doppler shifts to map out the movements of stars towards or away from us. For example, we find that galaxies rotate, so even if overall the galaxy is moving away from us, stars on one side of it may be less Doppler shifted than stars on the other side. When students examine different stars in different parts of the sky, they will make the discovery that almost all galaxies are shifted towards longer wavelengths, revealing that they are all moving away from us. Since longer wavelengths are closer to the red end of the visible spectrum, this effect is referred to as a 'redshift.'

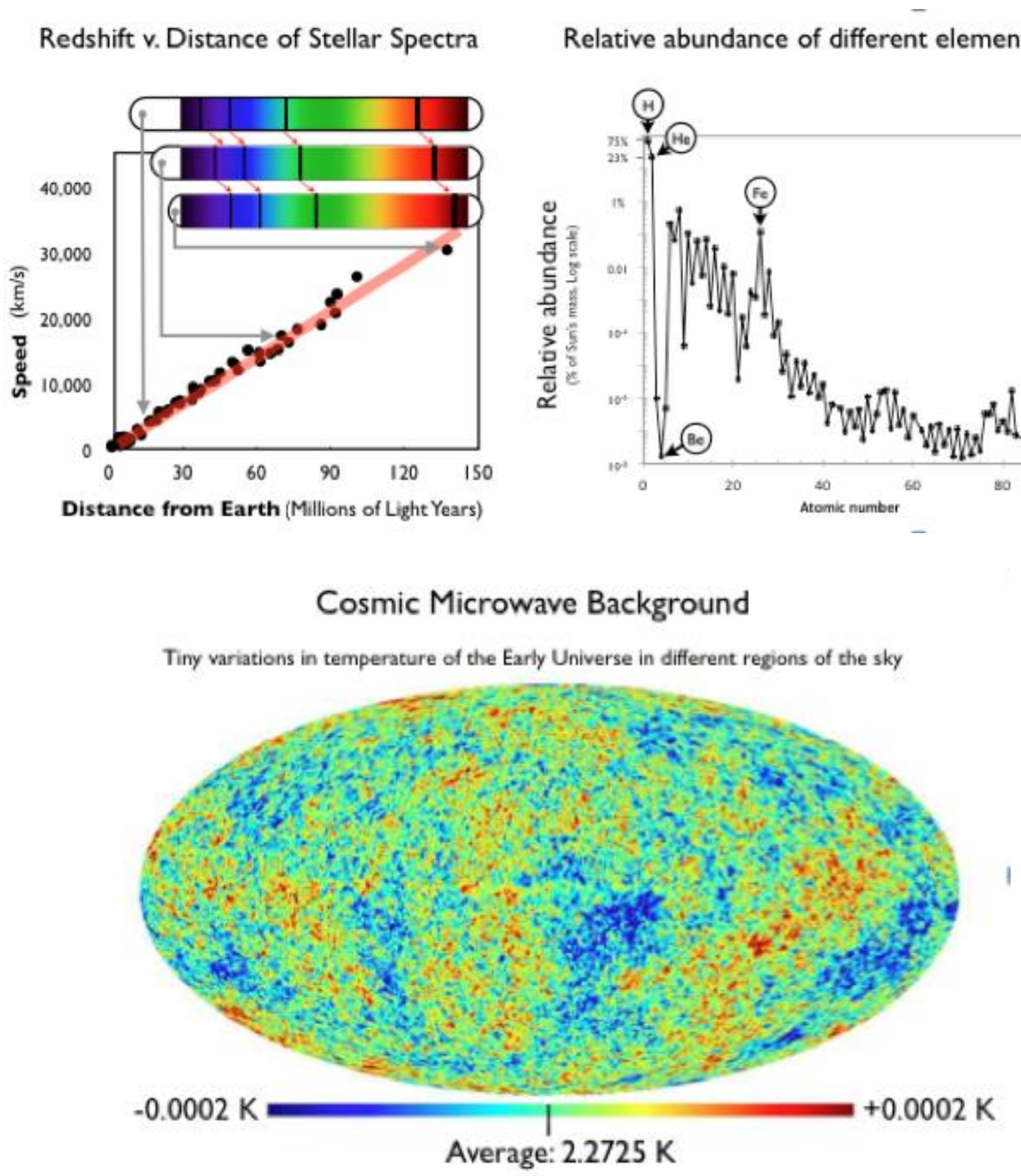
Students are now ready to **obtain information [SEP-8]** from media about Edwin Hubble's surprising discovery that the Universe is expanding (see Sloan Digital Sky Survey, The Expanding Universe at http://skyserver.sdss.org/dr1/en/astro/universe/universe.asp). At the time, scientists wondered if our Universe has always looked the way it does today. Einstein assumed a static, ungrowing Universe in his equations of relativity, but others like Willem de Sitter showed that an expanding Universe was also theoretically possible. Meanwhile, observational astronomers like Henrietta Leavitt developed techniques that allowed accurate distance measurements of objects in the Universe, and Vesto Slipher cataloged the redshifts of entire galaxies. Hubble entered the debate by combining these techniques and noticing a **pattern [CCC-1]** in the redshifts: the farther away a galaxy is from Earth, the faster it moves away from us. Some of the most distant galaxies have such an extreme red shift that they appear to be receding from us at a speed faster than the speed of light when we calculate their velocity using Doppler shift alone. If they were moving that fast, their light would never reach us and we wouldn't be able to see them. Hubble proposed a bold **model [SEP-2]** that could **explain [SEP-6]** this pattern in which galaxies are not really moving in space, but rather the space between the galaxies is getting bigger (much like a lump of dough expanding and moving mixed in raisins further apart from one another). The redshifts must be the combined effect of Doppler shift and the wavelengths getting stretched by the stretching of space itself!

Students can perform their own **investigation [SEP-3]** of redshifts using simulated telescope data from online laboratory exercises (Two older examples include Project CLEA at http://www3.gettysburg.edu/~marschal/clea/hublab.html or University of Washington Astronomy Department at http://www.astro.washington.edu/courses/labs/clearinghouse/labs/HubbleLaw/hubbletitle.html). That investigation requires an understanding of how distances are measured in the Universe, which builds on the **argument [SEP-7]** students constructed in fifth grade that the apparent brightness of stars in the sky depends on their distance from Earth (*5-ESS1-1*). Students can work independently or in small groups to **obtain information [SEP-8]** about one of the methods for determining distance in the Universe and then combine their findings with other students to develop a report, a poster, or a presentation that describes the **scale [CCC-3]** of the universe and how it is measured.

Students now have **evidence [SEP-7]** that the Universe is expanding, so teachers can invite them to **ask questions [SEP-1]** such as, “What is causing this expansion?” and “What would the Universe look like if we could ‘rewind’ this expansion to look back in time?” One possible model that could answer these questions is that everything that we can see as far as we can look out into the Universe was all once contained in a tiny region smaller than the size of an atomic nucleus! This region was so hot and dense at that time that it effectively exploded in what we call the Big Bang. We can see evidence of this explosion in the **matter and energy [CCC-5]** that exists in the universe today. Calculations by scientists reveal that the massive explosion would produce elements in specific proportions, and we can look for that fingerprint by using spectral lines to determine the relative abundance of different elements in stars like our Sun (graph in the top right in figure 7.68). While Sun’s relatively small proportion of heavier elements were formed in distant supernovas, its overall composition is similar to most other stars and matches the fingerprint predicted by the Big Bang with roughly three quarters hydrogen and one quarter helium.

In 1963, a group of scientists detected another piece of evidence of the Big Bang when they observed a constant stream of microwave radiation coming in every direction. They were worried it was something wrong with their equipment, but it became apparent that the signal they were detecting was also consistent with **models [SEP-2]** of a hot early universe that emitted radiation, which should still be traveling towards Earth today. We now call that **energy [CCC-5]** the Cosmic Microwave Background Radiation and can use it to get a picture of what the Universe looked like shortly after the initial Big Bang (image on the bottom in figure 7.68). Like so many scientific discoveries, engineering and technology have had a profound impact on scientists’ ability to make measurements. Students should be able to **explain [SEP-6]** each of these pieces of evidence and the model of the Big Bang, culminating the Physics of the Universe course by combining knowledge of electromagnetic radiation, nuclear processes, gravitational forces, and even conservation of momentum.

Figure 7.68. Evidence for the Big Bang



Evidence of the Big Bang comes from the redshift versus distance of stellar spectra (top left), the relative abundance of elements in the Sun determined from absorption spectra (top right), and the Cosmic Microwave Background Radiation that reveals minute differences in temperature in the early Universe (bottom). Sources: M. d'Alessio with data from Jha, Riess, and Kirshner 2007; M. d'Alessio with data from Lodders 2003; NASA 2008.

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